

Towards Resilient Cities through Digital Coupled Human, nAture and INfrastructure Systems (CHAINS)

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1 INTRODUCTION & SCOPE OF WORK

Worldwide, cities face unprecedented pressures to provide adequate resources, infrastructure, services, and resilience plans against the compounding threats of climate change. Urban management and development (UMD) must simultaneously benefit human populations while mitigating environmental impacts — a challenge that demands innovative, data-driven approaches. Digital Twins (DTs) have emerged as one of the most promising tools for tackling UMD challenges, enabling real-time monitoring, predictive modelling, and scenario analysis at the city scale [1]. However, existing DT frameworks often lack a unified theoretical grounding and fail to adequately integrate the complex interplay between people, nature, and infrastructure [2].

Based on many years of study, this research defines a DT from a data perspective as a dynamic virtual representation [3] integrating heterogeneous data sources to capture urban complexity across three key dimensions: (1) physical assets and city form; (2) processes, services and systems; and (3) human activities. This research addresses existing gaps by presenting a cohesive research programme centred on three interconnected contributions: (1) multi-modal data-driven digital twinning processes; (2) the Five-layer Multi-scale Digital Twin Theory incorporating People (FMDTT-People); and (3) the Road-Flood-User CHAINS (Coupled Human, nAture and INfrastructure Systems) digital twin. Together, these contributions chart a pathway towards next-generation resilient cities aligned with global sustainability goals.

2 METHODOLOGY

The research is structured around a three-part progressive framework, as illustrated in Figure 1. The framework is organised along two axes: abstraction level (from Algorithm/Technology at the base, through Theory/System, to Strategy at the top) and Information Richness Level (increasing from left to right). Part 1 establishes the data and algorithmic foundation through Digital Twinning; Part 2 introduces the theoretical framework of FMDTT-People to bridge the physical and digital worlds; and Part 3 operationalises these into urban resilience applications through the CHAINS digital twin. Each part builds upon the previous, forming a coherent pathway from data infrastructure to city-scale resilience strategy.

Multi-modal Data-driven Digital Twinning (Part 1): The first research strand develops automated pipelines that ingest and fuse multi-modal data — including point cloud, satellite imagery, IoT sensor streams, and social sensing data — to construct and continuously update semantic, information-rich DTs [4]. The focus is on enabling automatic semantic enrichment so that the DT remains current without manual intervention, thereby supporting real-time decision-making. The integration of static and dynamic data sources with AI-driven modelling forms the algorithmic and technological foundation of the overall framework.

Five-layer Multi-scale Digital Twin Theory — People (Part 2): The second strand proposes FMDTT as a theoretical framework that structures a DT across five hierarchical layers and explicitly introduces a People dimension. Stakeholder Requirements–Data Requirements (SR-DR)

mapping is used to establish bidirectional feedback loops between the physical and digital worlds. This ensures that citizens and urban stakeholders are not passive subjects of data collection, but active participants whose behaviours and needs shape and are shaped by the DT. FMDTT has been validated across multiple infrastructure scales — from individual buildings and hospitals to road networks and port systems [1].

Road-Flood-User CHAINS Digital Twin (Part 3): The third strand operationalises the above theory through the dynamic, people-centric Road-Flood-User CHAINS model. This framework couples hydrological flood modelling with road network vulnerability analysis and user behaviour simulation to represent the cascading, multi-hazard nature of climate-induced disaster chains [5]. By integrating real-time flood data, road closure information, and pedestrian/vehicle routing behaviour via GIS-Digital Twin and AI, CHAINS enables proactive and adaptive infrastructure resilience planning.

The overall research framework, illustrating the three-part progression and its strategic alignment with the UN SDGs, is summarised in Figure 1.

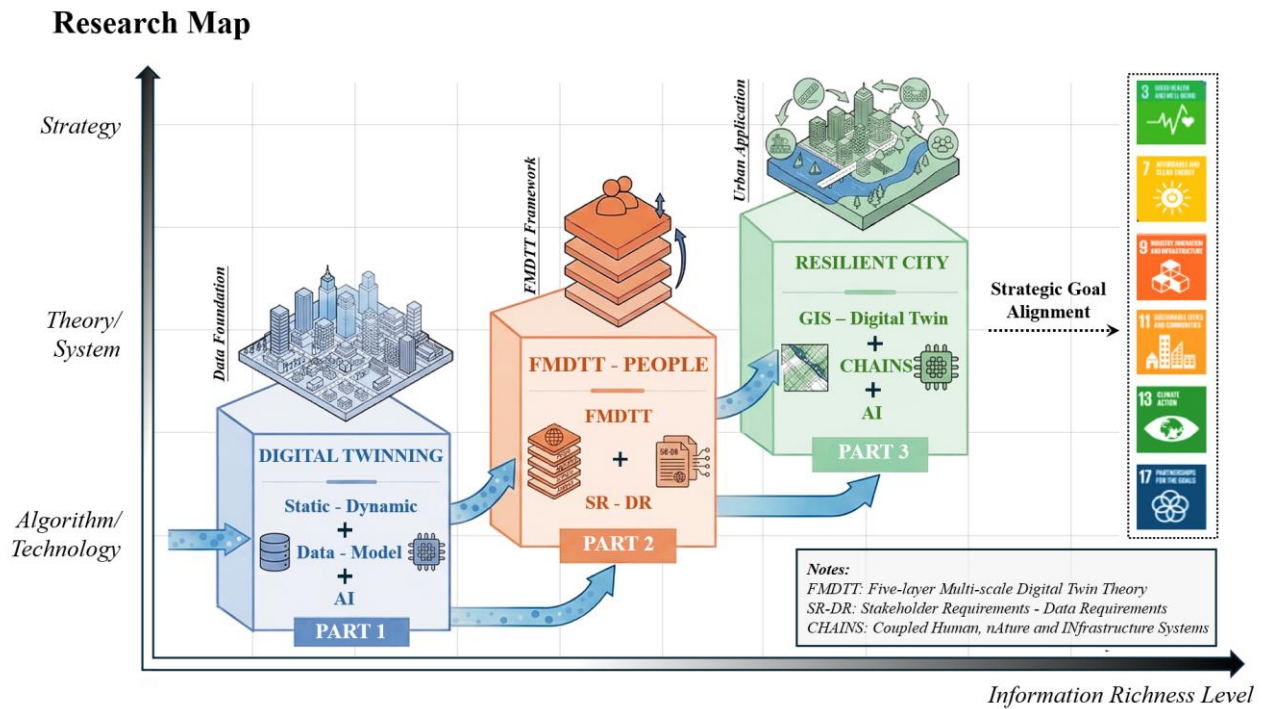


Figure 1. Research map presenting the three-part progression from Digital Twinning (Part 1) through FMDTT-People theory (Part 2) to Resilient City applications (Part 3), organised along axes of abstraction level and Information Richness Level, with alignment to UN SDGs 3, 7, 9, 11, 13 and 17.

3 RESEARCH OUTCOMES

The multi-modal twinning pipelines have demonstrated capacity for automated semantic updating across building and city-scale case studies, reducing manual modelling effort while increasing the temporal accuracy of DT representations. FMDTT has been adopted in both academic and industry contexts internationally, providing a transferable scaffold for DT development that explicitly accounts for human agency across multiple infrastructure scales. The Road-Flood-User CHAINS digital twin has been applied to real-world urban road networks subject to pluvial flooding events, showing improved resilience planning outcomes compared to conventional static hazard mapping approaches. The people-centric design enables dynamic rerouting recommendations and supports emergency response coordination. Collectively, this research offers a coherent pathway to align DT development with the UN Sustainable Development Goals (SDGs 3, 7, 9, 11, 13 and 17) [6] and the Sendai Framework for Disaster Risk Reduction [7]. Future directions include scaling CHAINS to multi-city contexts, integrating AI-driven predictive agents, and expanding the People layer to incorporate equity and accessibility dimensions.

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