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Tian, Y.; Soman, R. K.; Balakrishnan, S.; Bosch-Rekveldt, M.G.C.

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TOWARDS COMPLEX DIGITAL TWINS: CAPTURING EMERGENT BEHAVIORS IN INTERCONNECTED SYSTEMS

Stella Yongxue Tian[1], Ranjith K. Soman[1], Srijith Balakrishnan[2], and Marian Bosch-Rekveldt[1]
[1]Integral Design and Management, Delft University of Technology, Delft, The Netherlands
[2]Faculty of Technology, Policy and Management, Delft University of Technology, Delft, the Netherlands

Introduction

Infrastructure systems are increasingly shaped by interdependencies and emergent behaviors. These dynamics, intensified by climate change, urbanization, and technological advancement, demand rapid, holistic, and adaptive responses that traditional models often fail to provide (Mitchell, 2009). As illustrated by the 2025 California wildfire, such emergent phenomena—ranging from immediate impacts to secondary environmental risks— underscore the need for real-time, adaptive interventions (Entcheva, 2025; Mitchell, 2009; Peter and Swilling, 2014). While current DTs provide valuable insights within specific sectors (Tang et al., 2024), their isolated nature limits their capacity to reflect and manage broader systemwide behaviors. The growing body of literature highlights that digital twins must evolve to reflect these cross-domain interdependencies. Complexity science provides a valuable lens for understanding such systems, noting properties like self-organization, emergence, and adaptive feedback loops. By treating multiple digital twins as a single complex ecosystem, the paper discusses the theoretical underpinnings of Complex Digital Twins (CoDTs), defines their structure and variants, and illustrates their potential through real-world applications, aiming to guide future research, development, and governance in complex infrastructure environments.

Methodology

This study employs a Critical Interpretive Synthesis (CIS) approach to analyze and integrate diverse literature on digital twins and complex systems. The methodology is iterative and theory-driven, allowing for continuous refinement of the research question and sampling strategy. The process began with a broad scoping review, which identified a gap in understanding how interconnected digital twins form complex ecosystems. Guided by this gap, relevant literature was iteratively selected and coded using emergent themes. A coding framework was developed to identify recurring functional patterns and typologies, excluding narrow or redundant DT definitions. Through synthetic analysis, digital twin capabilities were systematically compared with characteristics of complex systems to develop a taxonomy of Complex Digital Twins (CoDTs). The method enabled the construction of a conceptual model that aligns DT evolution with complexity theory, providing a foundation for future research and practical implementation.

Evolving paradigms: from digital twins to complex systems

As a result of the literature review we found the evolution of digital twins (DTs) increasingly mirrors the defining characteristics of complex systems, prompting a reconceptualization of advanced DT implementations as CoDTs. Through a synthesis of recent literature, this study identifies key overlaps in purpose, function, and architecture between DTs and complex systems—such as autonomy, connectivity, emergence, and bidirectional feedback (Baldwin et al., 2011; Righi and Saurin, 2015). Modern DT developments exhibit two major trajectories: enhancing individual capabilities and enabling networked interoperability, both of which parallel behaviors in complex adaptive systems. By aligning DT advancements with complexity science, this work highlights how insights from systems thinking and socio-technical paradigms can inform the design and management of CoDTs. Recognizing digital twins as inherently complex systems not only clarifies their limitations but also opens new opportunities for adopting interdisciplinary approaches—such as agent-based modeling, adaptive governance, and resilience analysis—to better manage the uncertainties and dynamics of large-scale, interconnected infrastructures (Caldarelli et al., 2023; Karanikas and Chatzimichailidou, 2020).

Towards complex digital twin

To address increasing system complexity and unlock the full potential of digital twin technologies, this study proposes a three-tiered framework for Complex Digital Twins (CoDTs): the foundational CoDT, the Complex Adaptive Digital Twin (CADT), and the Complex Socio-Technical Digital Twin (CSTDT). These variants reflect escalating levels of integration, intelligence, and complexity. Their relations are shown in Figure 1. A basic CoDT involves interconnected digital twins that reflect and influence physical infrastructure components in real time, capturing emergent behaviors through feedback loops.

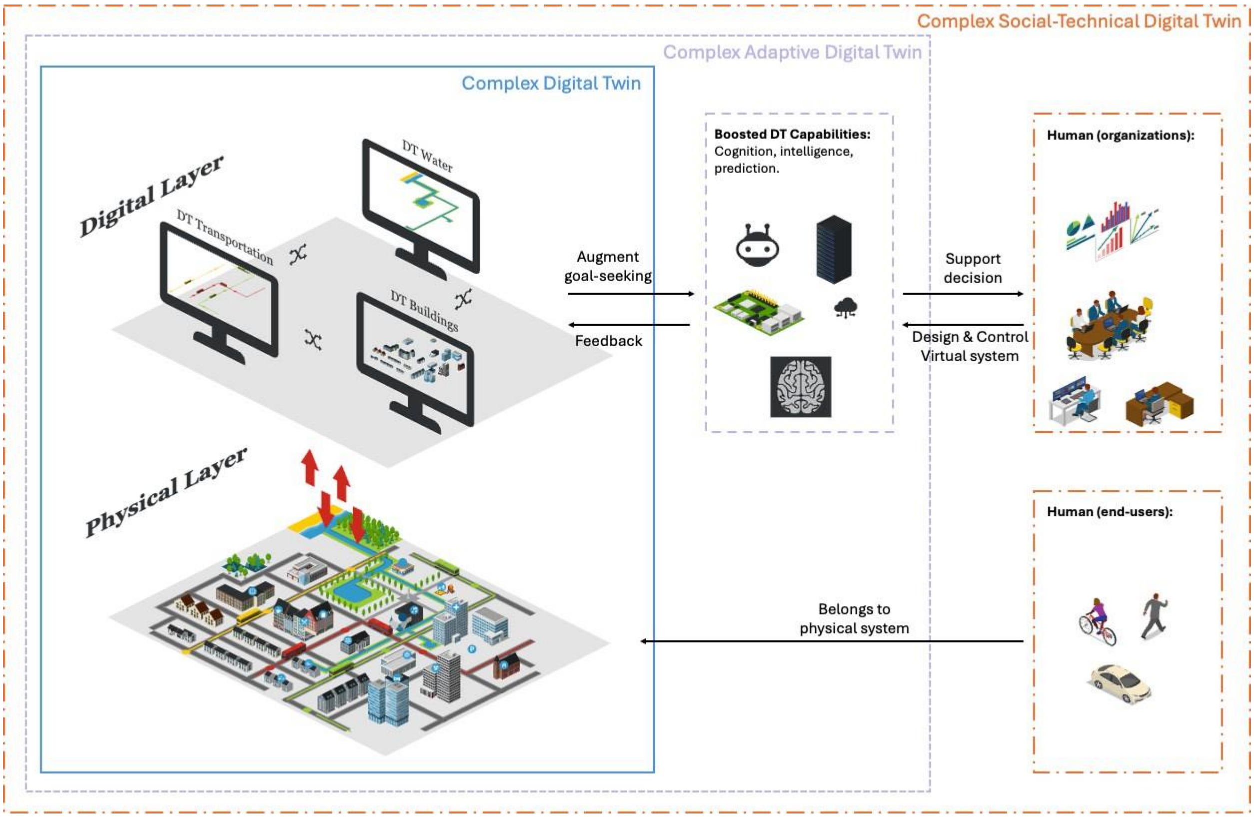

Figure 1:Complex Digital Twin Illustration

CADTs build upon this foundation by incorporating adaptive capabilities and AI-driven decision-making to enable dynamic, goal-oriented optimization. CSTDTs further extend this paradigm by explicitly integrating human and organizational dimensions, modeling socio-technical interactions to inform policy, governance, and stakeholder behavior. Together, these frameworks highlight a structured progression from technical integration to full-system adaptation and socio-technical alignment, offering a comprehensive model for managing complex infrastructure systems in uncertain and dynamic environments.

Use Cases

To illustrate the practical relevance of CoDTs, this study presents hypothetical use cases in intelligent transportation and critical infrastructure management. In intelligent transportation systems (ITS), CoDTs integrate real-time data from vehicles, infrastructure, and public transit to optimize traffic flow and respond dynamically to disruptions (Kouicem et al., 2018). Beyond mobility, regional CoDTs link water, energy, and communication networks to coordinate responses during extreme events, such as floods, by prioritizing resources and mitigating cascading failures. These examples highlight CoDTs' potential for adaptive, cross-domain management in complex environments.

Conclusion and Future Work

CoDTs are a necessary evolution from conventional digital twins, aligning them with complexity science to address the growing challenges of interconnected, socio-technical systems. The proposed framework offers both researchers and practitioners a structured approach to analyzing, designing, and implementing adaptive, cross-domain digital twin ecosystems. Future research directions include developing interoperability standards, exploring agent-based models for self-organization, and integrating sociotechnical policy frameworks to support large-scale CoDT deployment.

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