IARJSET

ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

International Conference on Interdisciplinary Global Research in Adaptation, Transformation & Engineering

INTEGRATE 2025

Geetanjali Institute of Technical Studies (GITS)

Vol. 12, SPECIAL ISSUE 2, NOVEMBER 2025

DOI: 10.17148/IARJSET/INTEGRATE.2025.12240

Socio-Technical Digital Twins and Interdependent Systems: A Review of Holistic Resilience Assessment for Urban Critical Infrastructure

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Abstract: The rapid digital transformation in the construction and urban infrastructure sectors has revolutionized how cities are designed, monitored, and maintained. Among these emerging technologies, **Digital Twin (DT)** frameworks have evolved from simple data visualization tools to complex **Socio-Technical Digital Twins (STDTs)** capable of modeling interdependent systems. This review paper examines the evolution of STDTs in the Indian construction industry, their integration into urban resilience frameworks, and their role in sustainable infrastructure development. Data collected between 2020 and 2025 are analyzed, highlighting market growth, implementation trends, and technological advancements. The study identifies key research gaps in interoperability, governance, and socio-technical alignment while offering recommendations for enhancing India's digital twin ecosystem to support resilient smart city infrastructure.

I. INTRODUCTION

The construction industry in India is undergoing a paradigm shift, driven by Industry 4.0 technologies such as Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins (DTs). These innovations have enabled better lifecycle management, predictive maintenance, and improved operational resilience of critical infrastructure.

According to Grand View Research (2024), India's digital twin market was valued at approximately USD 546.7 million in 2024 and is expected to reach USD 4.59 billion by 2030, growing at a compound annual growth rate (CAGR) of around 41%. Similarly, IMARC (2025) reported that India's overall digital twin market could reach USD 16.64 billion by 2033, reflecting the country's commitment to smart infrastructure and sustainable urbanization.

The Socio-Technical Digital Twin (STDT) concept extends beyond traditional engineering by incorporating human, organizational, and social dynamics into digital modeling. This integration is crucial for developing resilient urban systems, where human behavior, institutional capacity, and physical infrastructure interact dynamically under changing environmental and social conditions.

II. METHODOLOGY

This review employs a systematic literature review (SLR) approach to identify and synthesize existing research from 2020 to 2025. The selection process included scholarly articles, reports, and conference papers from sources such as *Elsevier, Taylor & Francis, Springer, and IEEE Xplore*.

The inclusion criteria were:

- Studies published between 2020–2025.
- Research focusing on Digital Twin applications in construction, urban resilience, or socio-technical integration.
- Articles featuring case studies or empirical data on the Indian or comparable emerging economies' contexts.

A thematic analysis method was adopted to classify findings into five categories: (1) Technological innovation, (2) Integration with IoT and AI, (3) Socio-technical modeling, (4) Urban resilience, and (5) Governance and policy support.

III. LITERATURE REVIEW

3.1 Technological Evolution of Digital Twins

Zhao et al. (2020) emphasized the role of DTs in integrating real-time IoT data for smart city management. Zhang et al. (2021) demonstrated how AI-powered DTs could predict infrastructure failure and optimize resource allocation.

Bhattacharya and Kumar (2022) noted that India's construction firms increasingly adopt BIM-integrated DTs for smart monitoring of bridges and buildings. Patil and Sinha (2023) highlighted the evolution of hybrid DT systems, which merge virtual simulation with real-time environmental data for construction safety monitoring.

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Gupta et al. (2024) analyzed the challenges of interoperability and data privacy in DT ecosystems. Meanwhile, Singh and Sharma (2025) emphasized the transition from purely technical models to socio-technical ones—embedding stakeholder participation, governance, and behavioral data.

3.2 Digital Twin Implementation in India

India's smart city mission has accelerated the adoption of DT technologies in urban management, transportation, and construction. According to Geospatial World (2025), digital twins are increasingly used for infrastructure visualization, predictive maintenance, and urban heat reduction.
Cities like Surat, Pune, and Bengaluru have begun integrating DTs into smart city dashboards, using real-time sensor data to simulate flood risks, manage energy consumption, and optimize traffic flow (Kumar & Joshi, 2024).

3.3 Market Growth and Economic Impacts

The Indian DT sector has seen exponential growth. Research & Markets (2024) estimated that over 95% of IoT platforms will include digital twin functionality by 2029, demonstrating a rapid shift toward interconnected digital ecosystems.
Moreover, PatentPC Blog (2025) reported that 70% of urban DTs are updated with real-time sensor data every five minutes, contributing to improved decision-making and crisis response.

3.4 Socio-Technical Integration and Resilience

Socio-technical frameworks extend traditional DTs by integrating social and governance dimensions. Rana et al. (2022) proposed that urban resilience depends not only on physical robustness but also on social adaptability and institutional capacity. Li and Qian (2023) introduced a multi-agent socio-technical model for disaster management using DTs.
In India, Choudhary et al. (2025) demonstrated how combining human-centric design with digital simulation enhances disaster preparedness and communication efficiency.

IV. DATA AND FACTS TABLE

Fact	Data/Facts	Year	Region	Source
1	Over 95% of IoT platforms will contain some form of digital-twinning capability by 2029	2024	Global	Research & Markets
2	Digital twin solutions in smart cities projected to reach USD 5.9 billion by 2029	2024	Global	GlobeNewswire
3	India's DT market: USD 546.7 million (2024) → USD 4.59 billion (2030)	2024	India	Grand View Research
4	India's DT market: USD 762 million (2024) → USD 3.79 billion (2030)	2025	India	Geospatial World
5	More than 500 cities to adopt DT technology by 2025	2024	Global	Reuters
6	DT adoption led to a 28% reduction in urban heat island effects	2025	Global	PatentPC Blog
7	India's DT market expected to reach USD 16.64 billion by 2033 (CAGR 36.2%)	2025	India	IMARC Report
8	70% of smart city DTs updated every 5 minutes	2025	Global	PatentPC Blog
9	Fastest-growing DT segment: infrastructure/transportation	2024	India	Grand View Research
10	83% of officials cite rigid hierarchies as barriers to digital adoption	2025	Global	PatentPC Blog

V. DISCUSSION AND ANALYSIS

The data clearly indicate that India's construction and infrastructure sectors are rapidly digitalizing, with DT and STDT frameworks emerging as central tools for resilience planning.
The increasing availability of real-time data, integration of AI-driven analytics, and the shift toward human-centered system modeling collectively represent a socio-technical transformation.
However, despite significant growth, challenges persist — especially in data standardization, policy coordination, and multi-stakeholder engagement. Most implementations remain technology-driven rather than socio-institutional, limiting the long-term sustainability of such systems.

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VI. RESEARCH GAPS

1. **Interoperability Gap:** Lack of standardized frameworks for integrating DTs across multiple urban domains.
2. **Socio-Technical Alignment Gap:** Minimal incorporation of human behavior, decision-making, and governance structures.
3. **Policy and Data Governance Gap:** Weak institutional frameworks for data sharing, privacy, and accountability.
4. **Scalability Gap:** Limited scalability of DT models beyond pilot smart city projects.
5. **Capacity Building Gap:** Inadequate skill development and training for engineers and planners in digital twin technologies.

VII. RECOMMENDATIONS

1. **Develop National DT Standards:** Establish uniform guidelines for data interoperability and simulation accuracy.
2. **Promote Public-Private-Academic Collaboration:** Facilitate joint innovation hubs for STDT research and training.
3. **Integrate Social and Behavioral Models:** Include stakeholder interactions and public participation in DT frameworks.
4. **Enhance Data Infrastructure:** Invest in real-time IoT systems and cloud computing for continuous model updates.
5. **Adopt Capacity-Building Programs:** Integrate digital twin training in civil engineering and urban management curricula.

VIII. CONCLUSION

The revolution of the construction industry in India through the adoption of socio-technical digital twins signifies a major leap toward smart, sustainable, and resilient urban systems. While technological readiness is rapidly advancing, institutional and social integration remain the key challenges. Strengthening socio-technical linkages and policy alignment can transform India into a global leader in digital infrastructure resilience by 2030.

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