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Review

Integrating Social Dimensions into Urban Digital Twins: A Review and Proposed Framework for Social Digital Twins

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Highlights

What are the main accomplishments of this study?

- Provides a comprehensive literature review on social digital twin (SDT) concepts, features, key technologies, and analytical tools, and highlights research gaps and practical challenges.
- Proposes an SDT framework and governance model designed to address the limitations of current urban digital twins (UDTs) by integrating social dimensions throughout the process.

What are the implications of this study?

- Transforms UDTs by advancing dynamic, holistic models that go beyond representing physical “spaces” to capturing the full “place”, including both physical and social dimensions, in real time. This improves the conceptualization, modeling, and practical applications of SDTs.
- Promotes a socially inclusive governance model for smart city management through the SDT framework, offering valuable guidance for researchers, decision-makers, and technology developers, while enabling cities to better meet urban social needs.



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Abstract: The rapid evolution of smart city technologies has expanded digital twin (DT) applications from industrial to urban contexts. However, current urban digital twins (UDTs) remain predominantly focused on the physical aspects of urban environments (“spaces”), often overlooking the interwoven social dimensions that shape the concept of “place”. This limitation restricts their ability to fully represent the complex interplay between physical and social systems in urban settings. To address this gap, this paper introduces the concept of the social digital twin (SDT), which integrates social dimensions into UDTs to bridge the divide between technological systems and the lived urban experience. Drawing on an extensive literature review, the study defines key components for transitioning from UDTs to SDTs, including conceptualization and modeling of human interactions (geo-individuals and geo-socials), social applications, participatory governance, and community engagement. Additionally, it identifies essential technologies and analytical tools for implementing SDTs, outlines research gaps and practical challenges, and proposes a framework for integrating social dynamics within UDTs. This framework emphasizes the importance of active community participation through a governance model and offers a comprehensive methodology to support researchers, technology developers, and policymakers in advancing SDT research and practical applications.

Keywords: social digital twin; urban digital twin; human digital twin; smart city; smart governance; citizen participation; framework

1. Introduction

In our contemporary era dominated by modernization and technological advancements, the “smart city” has emerged as a transformative concept in urban development, integrating technologies such as urban digital twins (UDTs) [1–3]. However, most UDTs remain focused on the physical aspects of urban environments, often overlooking the interconnected social dimensions that define urban “place” [4,5]. This limitation restricts their ability to fully capture the complex interactions between infrastructure and social systems, reducing their effectiveness in addressing urban challenges [6,7]. Bridging this gap is essential for developing more holistic and inclusive urban models [8,9].

A key characteristic of a smart city lies in its ability to harness the power of digitalization, connectivity, and information technologies to efficiently manage urban activities, tackle urban challenges, and optimize city services and living conditions [10,11]. By integrating advanced technologies with data-driven solutions, smart cities aim to enhance the overall efficiency, sustainability, and quality of life for their residents [12,13]. Noteworthy contributors regard smart cities as complex systems, involving the interplay among people, institutions, organizations, technology, and physical built environments, highlighting their inherently holistic nature [14–18].

The concept of smart cities has evolved over the years, originating from research on intelligent urban environments and focusing on innovative sociotechnical and socio-economic growth [19]. Kaminionos described three phases of smart city development. The first phase, Smart City 1.0, is characterized by technology-driven projects led by Information and Communication Technology (ICT) companies, often implemented without considering the specific needs of cities. In Smart City 2.0, public administration takes the lead, using technology to improve citizens’ quality of life. The more recent phase, Smart City 3.0, emphasizes citizen-centered approaches, integrating social, educational, and ecological considerations while maintaining a focus on technological innovation and citizen participation [20]. Emerging now is Smart City 4.0, driven by new economic models and highlighting the dynamic evolution of smart city concepts toward sustainable development [21,22].

The integration of smart city projects into the built environment can be essential for optimizing urban functionality and service quality [23]. A key step in achieving this integration is the effective understanding and conceptualization of the city and its components, which is well supported by digital twin (DT) technology [24–26]. In recent years, DTs have emerged as a powerful tool for managing complex urban systems, enabling advanced monitoring, simulation, optimization, and prediction of cyber–physical systems [27]. Since its inception in 2002, the DT concept has evolved from an idea introduced by Michael Grieves within manufacturing to a widely applicable technology redefined in 2012 by Grieves and John Vickers as a “digital representation of a physical asset and the real-time connections that bind them together” [28,29].

DTs can be categorized by functionality, with static twins modeling structural dependencies such as physical attributes and layouts to provide foundational visualizations, and behavioral twins emphasizing dynamic connectivity to simulate real-time processes and interactions, capturing the evolution of systems [30–32]. Many DTs combine these elements for versatile urban modeling. Initially applied to industrial processes, the DT concept has expanded to a wide range of applications across various fields [31]. Over time, it has been adapted to urban contexts, giving rise to urban digital twins (UDTs). UDTs now serve

as comprehensive platforms for managing buildings, neighborhoods, and entire cities by integrating physical, digital, and, in some cases, social dimensions. They offer real-time insights and innovative solutions to address complex urban challenges [33–36].

Historically, UDTs focused on modeling physical infrastructure—such as buildings, transportation networks, and utilities—while addressing environmental concerns to drive economic success [37–41]. However, this approach often treated the social dimensions as separate, limiting the capacity of these systems to comprehensively represent urban dynamics [4,5]. Today, UDTs are evolving to include socio-environmental processes, which link urban form, human behavior, and ecological dynamics. For instance, UDTs can simulate how changes in urban design affect social mobility, public health, and community resilience, while also addressing environmental challenges like air pollution and resource scarcity [37,41–46].

Despite its widespread adoption, the current definition of a UDT falls short in the context of cities, which are inherently social systems rather than purely physical entities [9,47,48]. Unlike automated systems, cities are dynamic environments that continuously evolve across physical, economic, political, social, cultural, and ecological dimensions [3,5,49,50]. That is to say, existing UDT models related to smart cities often emphasize the physical aspects of the built environment, or “space”, while overlooking the “place”, which includes the emotional, cultural, and social meanings that people assign to their surroundings [6,7,51–53]. This interprets results in UDTs struggling to simulate, manage, or predict social processes effectively.

Implementing an integrated space–place approach, as outlined in the Urban Quality Space–Place Framework presented in [53], offers a pathway to more holistic UDTs by redefining the built environment to include interconnected physical and social characteristics, reflecting their mutual influence and their digital replications. While “space” provides an objective structure, “place” transforms it into a meaningful, lived experience shaped by perceptions, interactions, and social dynamics. Central to this integration are the concepts of geo-individuals—individuals situated within specific space–time contexts—and geo-socials, which extend this perspective to include social interactions and collective experiences. Together, these concepts form the livability field, a dynamic system reflecting inclusion, exclusion, and social cohesion within urban areas [53].

Furthermore, the current UDT process remains technically oriented, prioritizing the physical aspects of urban environments while relegating the social dimensions to a secondary status [47,54]. As a result, existing models lack adequate digital representations of human interactions, highlighting a significant disconnect between urban systems and the lived experiences they aim to replicate—concepts encapsulated by geo-individuals and geo-socials. This gap is further exacerbated by the dominant technocratic, top-down approach of many smart city DT projects, which often prioritize governmental and corporate interests over those of citizens [55,56]. Limited citizen participation in these processes widens the disparity between digital models and urban realities, raising critical questions about how well these systems reflect residents’ needs and interactions with cities [56–60]. Consequently, the absence of social integration in UDTs has sparked a growing but under-explored research area focused on addressing these social dimensions—what we now refer to as the social digital twin (SDT).

This paper introduces SDTs as a transformative concept for integrating social dimensions into UDT models, addressing critical gaps in current UDT research. By redefining UDTs from digital representations of “space” to comprehensive constructs of “place”, the study incorporates social dynamics into traditionally technical and physical models. This reimagining aims to establish SDTs as an innovative paradigm for bridging the gap between physical–technical modeling and social considerations. The research makes three key contributions: first, it enhances the conceptualization and modeling of SDTs by embed-

ding human perspectives to improve the management, prediction, and representation of social dynamics in urban systems; second, it strengthens citizen input and participation by proposing a decentralized, bottom-up approach to governance to better align smart city systems with community needs; and third, it extends UDT applications by embedding social considerations into domains previously dominated by spatial and technical analyses. The paper provides an overview of essential features and SDT-related tools (foundational technologies and specialized analytical tools). Additionally, it identifies existing research gaps and practical challenges while proposing a comprehensive SDT framework and governance model for embedding social dimensions within UDT models. By shifting the paradigm of UDTs from a predominantly space-centric model to one designed for the entire urban place, this research aims to enhance both the social relevance and operational effectiveness of UDT systems. The outcomes aim to support researchers, technology developers, and policymakers in advancing SDT research and practical applications.

2. Materials and Methods

The methodology of this paper is organized into seven sections, each building towards a comprehensive framework for integrating social dimensions into UDTs through the concept of SDTs (Figure 1). The research begins by conducting a systematic literature review on SDTs to analyze relevant studies and identify knowledge gaps in the existing research landscape. Building on the review, the paper moves from UDT to SDT by identifying key social and physical components within the UDT context, laying a foundational understanding of how human behavior, interactions, and community engagement contribute to urban digital models. This initial step establishes a socio-technical perspective necessary for understanding SDTs' integration into UDTs.

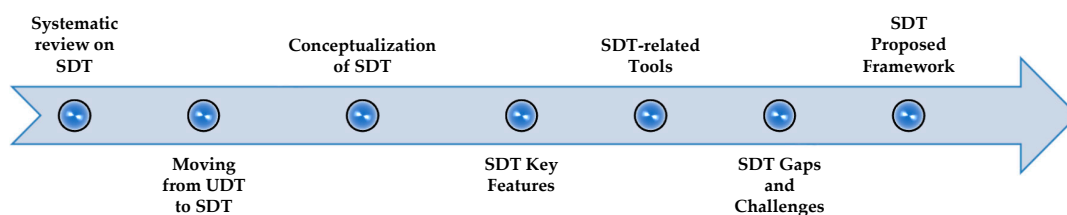


Figure 1. Adopted methodology.

Following this, the paper delves into a clear definition and multidimensional conceptualization of SDTs to offer a comprehensive understanding of SDTs as a socio-technical construct. Core features of SDTs, from their characteristics to applications, are then outlined. Next, the paper addresses the tools related to SDTs. This section reviews foundational technologies and specialized analytical tools and their role in supporting SDT functions, from data collection and processing to visualization and interaction.

Following this, the paper identifies the main research gaps and practical challenges of SDTs. By highlighting these obstacles, the study creates a foundation for proposing effective solutions that address these gaps and challenges. Finally, the paper synthesizes insights from the preceding sections to propose a comprehensive framework for incorporating social dimensions into UDTs.

The paper targets three key groups with tailored insights. Academic researchers in fields like urban studies, artificial intelligence (AI), and social sciences applied theoretical concepts, proposed interdisciplinary applications, and identified research gaps to advance scholarly discourse and inspire future studies. Policymakers and urban planners benefit from practical applications of SDTs in urban contexts, enabling evidence-based policymaking and responsible SDT integration. Technology developers and industry practitioners, such as engineers and IT professionals, are provided with technical architectures and opera-

tional guidelines to design, implement, and scale socially adaptive SDT systems effectively. This multidimensional approach fosters collaboration across academia, policy, and industry for holistic SDT development.

To ensure the quality and accuracy of the findings, the data and results were thoroughly reviewed and discussed with experts specializing in smart cities and digital twins. These experts provided valuable feedback on the search results and content analysis, which was carefully incorporated into the final version of the extensive literature review. Additionally, OpenAI was used only to enhance text readability, with all content subsequently reviewed and edited as necessary.

2.1. Systematic Review on Social Digital Twins

The systematic review process began by scoping the current literature on the SDT using Scopus and Web of Science databases, covering studies published up to September 2024. The primary objective was to address a key question: What are the definitions and dimensions of a social digital twin at the urban scale within the smart city framework? To answer this, the first step involved identifying relevant papers using specific keywords that included “social digital twin” OR “human digital twin” AND “smart city” AND “urban”. This search yielded a total of 144 publications, including journal articles, conference proceedings, review papers, and book chapters. Following the initial search, an exclusion process was conducted to filter out duplicated or redundant materials. A total of 69 publications were removed. This refinement left 75 papers for further evaluation. To ensure comprehensive coverage of the topic, a supplementary manual search using Google Scholar was also conducted, identifying 9 additional relevant papers. This brought the total number of publications to 84 for further assessment.

Next, the titles and abstracts of these 84 papers were screened to determine their relevance to the research question. The focus was on studies that explicitly addressed the integration of social dimensions into DTs within smart cities. As a result, 31 papers were excluded, either because they were irrelevant or due to the unavailability of full-text access. This left 53 papers for a detailed evaluation. These remaining papers then underwent a full-text assessment, where they were examined for their relevance, methodology, and contribution to the understanding of the social digital twin concept. During this phase, 23 papers were eliminated because they did not meet the criteria for relevance or depth concerning social aspects of DT technologies. Finally, 30 papers were deemed eligible for inclusion in the detailed review. A summary of the systematic review process is illustrated in Figure 2.

2.2. From Urban Digital Twin to Social Digital Twin

A smart city integrates digital technologies, particularly ICT, to enhance operational efficiency, sustainability, and quality of life [10,11]. UDTs embody these principles by creating dynamic, data-driven environments that enable real-time monitoring and control of urban systems, optimize resource use, and foster collaboration among city planners, citizens, and policymakers [1,50,61]. Acting as the central “brain” of smart cities, UDTs are essential for coordinating and optimizing interconnected urban systems.

UDTs inherently involve multiple dimensions, including technological, environmental, economic, and social. The technological dimension underpins real-time data collection, processing, and analysis, while the environmental, economic, and social dimensions address sustainability [50,54,62–65]. Among these, the social dimension—relating to citizens and decision-making processes—is central to understanding SDTs.

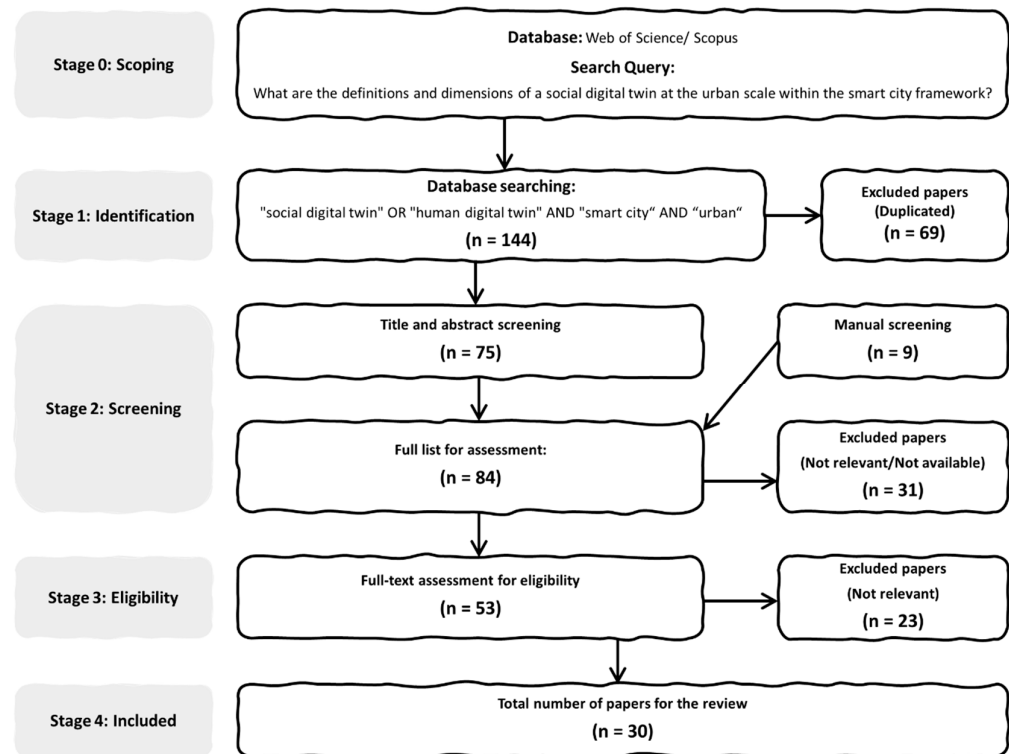


Figure 2. Systematic review process.

To grasp the concept of a SDT, it is important to position it within the broader context of a UDT. While there is no universally accepted definition of a UDT, some recognized definitions do exist, such as the one proposed by [66], which describes a UDT as a “realistic digital representation of assets, processes, or systems in the built or natural environment”.

In the current literature, there is significant emphasis on the physical components of UDTs, which are considered essential in all studies. However, social components are often treated as complementary, rather than integral, to UDT systems. Based on a review of the state of the art, three core components can be determined as forming the foundation of UDTs: the physical realm, the digital realm, and the real-time connection. Each of these components includes respective subcomponents, which together provide a comprehensive understanding of how physical and, in some cases, social components interact within a UDT system. Collectively, these components and their subcomponents form the complete UDT system, as illustrated in Figure 3.

- **Physical Realm:** This realm should ideally integrate both physical and social components. The physical dimension includes tangible elements such as physical systems (e.g., buildings and infrastructure), the physical environment (the surroundings where these systems exist), and physical processes (operational activities such as infrastructure maintenance) [31,66–74]. The social dimension focuses on humans (geo-individuals) and their interactions at the society level (geo-socials) with these physical systems, including relationships between people, stakeholders, and their environments [4,53,63,75–78]. This integration grounds UDTs in the reality of urban dynamics.
- **Digital Realm:** The digital realm represents the virtual counterpart of the physical world, including virtual systems (digital models of physical entities), the virtual environment (a simulated world replicating real-world conditions), and virtual processes (computational tools for simulating operational activities) [31,66–74]. On the social side, some studies highlight the importance of capturing digital human representa-

- tions (digital geo-individuals) and virtual human interactions at the society level (geo-socials), enabling simulations of human behavior and its social impacts [4,53,63,75–78]. This capability allows UDTs to simulate and optimize complex urban systems effectively.
- **Real-Time Connection:** This component enables continuous synchronization and data exchange between the physical and digital realms through physical-to-virtual connections (data collection and digital representation) and virtual-to-physical connections (feedback to the real world) [8,28,31,66–75,79–84]. Key performance metrics, such as twinning rate (frequency of updates) and fidelity (precision and granularity of data exchange), ensure accurate, real-time representation and feedback between the two realms [69,72,73,83,84].

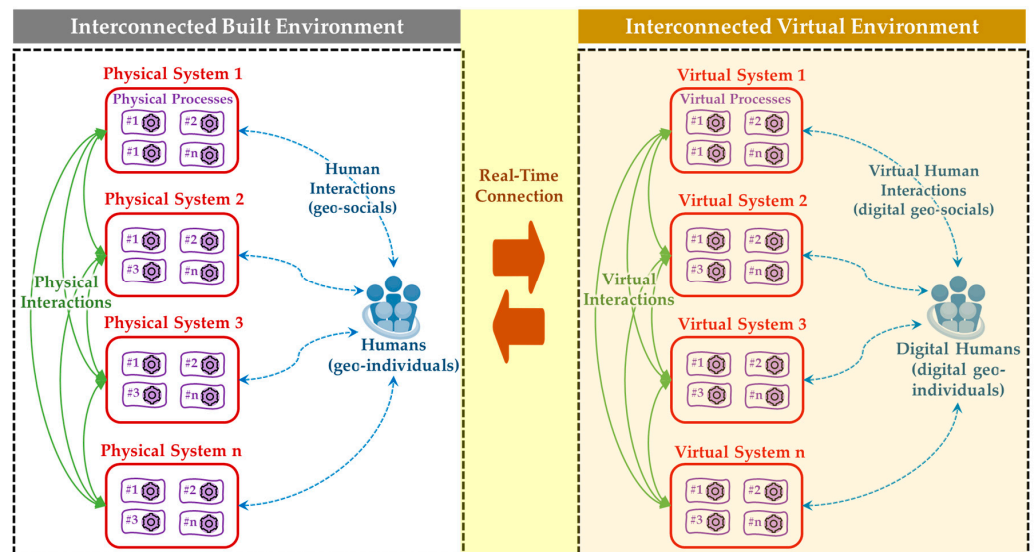


Figure 3. Depiction of the key components of the UDT.

Despite the advancements, current UDT processes remain predominantly technically oriented, prioritizing the physical aspects of urban environments, or “space”, while relegating social dimensions—representing the “place”—to a secondary status. Social aspects are often considered as separate dimensions, indirectly related to the physical and digital realms through human interactions (Figure 4). However, they should be an inherent part of UDT systems to fully represent the multidimensional concept of “place”.

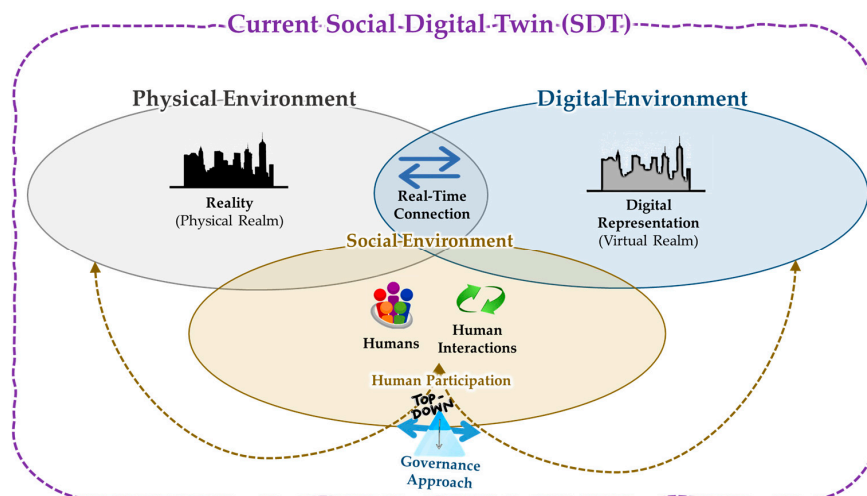


Figure 4. Depiction of the current SDT.

Furthermore, discussions about SDTs lack clarity and organization, particularly regarding their integration into the broader UDT concept. A new structured framework for SDTs is needed to guide their design, implementation, and evaluation. This framework should outline essential steps, components, and governance systems to ensure their effective operation and integration within UDT systems. Such a framework will be invaluable for researchers, technology developers, and decision-makers, providing a comprehensive methodology for advancing SDTs and their applications in future research and practice.

3. Results

3.1. Conceptualization of Social Digital Twins

The concept of the SDT, sometimes also referred to as the human digital twin (HDT), emerges from a convergence of social, technical, and physical aspects within the broader framework of a UDT. To clarify its core principles, the paper draws on insights from a comprehensive literature review of current research in this area conducted through a systematic approach. The SDT extends the traditional UDT concept, which typically revolves around the physical realm, digital realm, and their interconnections, by incorporating social dimensions. This enriched model integrates human behaviors, interactions, and social networks, making social dynamics a foundational aspect of urban modeling. This integration introduces the notion of parallel societies, where real-world physical and social systems are mirrored and interact dynamically in a virtual environment through SDTs [85]. This approach shifts the perception of urban systems from merely physical “spaces” to comprehensive, dynamic “places” that encapsulate both tangible and intangible dimensions [86]. Such a transformation facilitates improvements in performance, well-being, and decision-making [4].

Based on the reviewed literature, the SDT can be defined as a system designed to replicate and represent social aspects through various stages. From conceptualization to application, the SDT functions as a dynamic virtual representation of an urban environment, seamlessly integrating physical and social elements via bidirectional, real-time connectivity. Central to this model is its ability to reflect the interplay between physical systems and humans (referred to as geo-individuals), as well as societal interactions at a macro level (geo-socials), as illustrated in Figure 5.

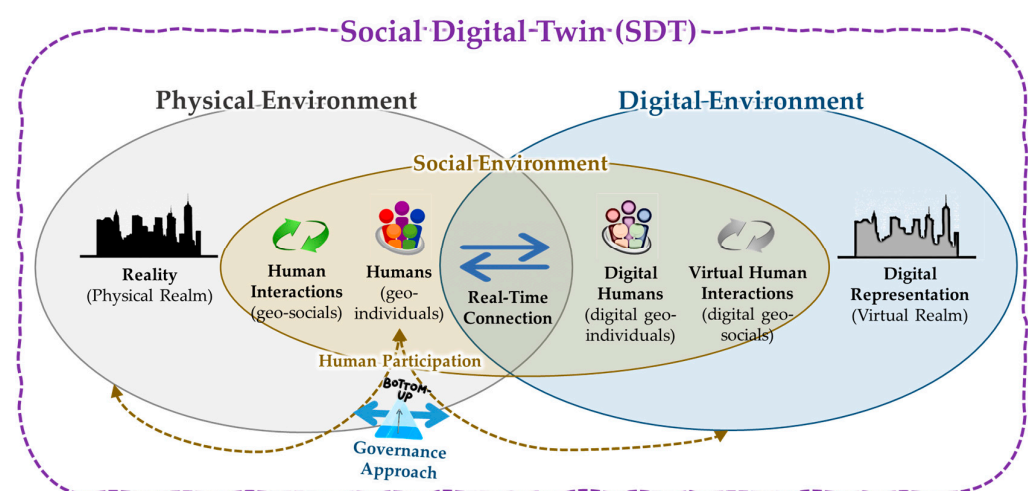


Figure 5. Depiction of the ideal SDT.

To address the issues of clarity and organization in the various aspects of SDTs, they are categorized into a process-based structure comprising three main stages: Conceptualization, Modeling, and Application. The Conceptualization Stage involves defining goals, exploring

relevant theories, and collecting data. Following this, the Modeling Stage focuses on managing social data, performing analyses, and developing visualizations to represent social dynamics effectively. Finally, the Application Stage encompasses decision-making processes, incorporating feedback mechanisms, and fostering interaction within the system.

Additionally, effective governance structures play a key role across all these phases, along with social inputs that are equally vital, forming the foundation of the SDT’s representation of urban systems and enabling a cohesive integration of social dynamics into the overall SDT structure. This organizational structure is illustrated in Figure 6.

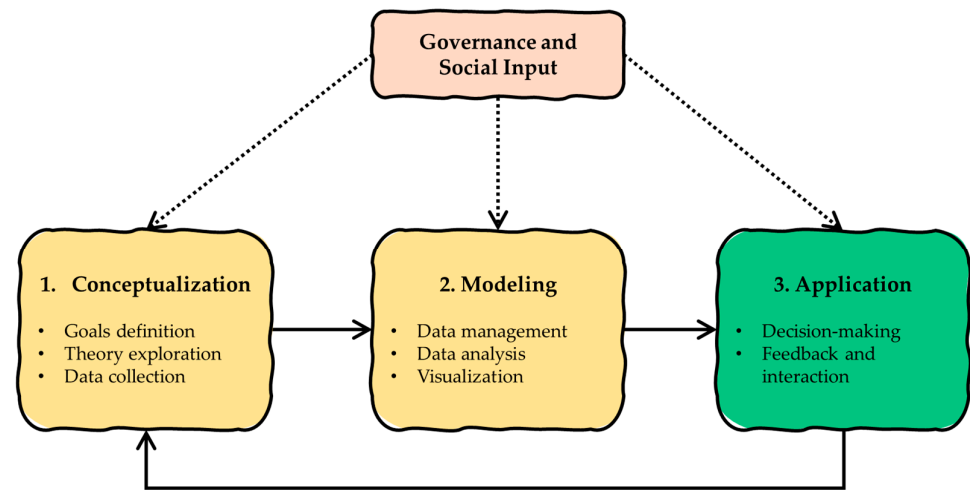


Figure 6. Organizational structure of the SDT system.

To develop a multidimensional conceptualization of the SDT, we draw on findings from the systematic review. Table 1 presents a summary of the key insights from the 30 reviewed papers, detailing each paper’s title, primary focus, and specific emphasis within the SDT concept.

Table 1. A summary of the key insights from the 30 reviewed papers, including titles, primary focus, and specific emphasis within the SDT concept. Note: The paper may cover multiple focus areas, but the area marked with * indicates the primary focus.

No.	Authors	Title	Main Focus of Paper	SDT Focus Area		
				Concept and Modeling	Governance and Social Input	Social Applications
1	(F.-Y. Wang et al. 2020) [85]	Parallel societies: A computing perspective of social digital twins and virtual–real interactions	Parallel Societies: SDTs and Virtual–Real Interactions	X *		X
2	(Chukhno et al. 2020) [87]	Optimal placement of social digital twins in edge IoT networks	SDTs for IoT Networks	X		
3	(Barn 2022) [47]	The Sociotechnical Digital Twin: On the Gap between Social and Technical Feasibility	Sociotechnical DTs	X *	X	

Table 1. Cont.

No.	Authors	Title	Main Focus of Paper	SDT Focus Area		
				Concept and Modeling	Governance and Social Input	Social Applications
4	(Bomström et al. 2022) [4]	Digital twins about humans—design objectives from three projects	Human DTs		X	
5	(Abdeen and Sepasgozar 2022) [88]	City digital twin concepts: A vision for community participation	Community Participation in Smart City DTs		X *	X
6	(Lin et al. 2022) [77]	Human Digital Twin: A Survey	Human DTs	X *		X
7	(Charitonidou 2022) [86]	Urban scale digital twins in data-driven society: Challenging digital universalism in urban planning decision-making	UDTs in a Data-Driven Society	X *	X	X
8	(Botín-Sanabria et al. 2022) [89]	Digital Twin Technology Challenges and Applications: A Comprehensive Review	Physical and Social Integration of DTs in City Planning	X	X *	X
9	(Chukhno et al. 2022) [90]	Placement of social digital twins at the edge for beyond 5G IoT networks	SDTs for Beyond 5G IoT Networks	X		
10	(Barachini and Sary 2022) [91]	From digital twins to digital selves and beyond: Engineering and social models for a trans-humanist world	Sociotechnical DTs for a Trans-humanist World	X		
11	(Lv et al. 2022) [92]	Building the metaverse using digital twins at all scales, states, and relations	Social Interaction DTs in the Metaverse	X		
12	(Adade and de Vries 2023) [63]	Digital Twin for Active Stakeholder Participation in Land-Use Planning	Integration of Social Aspects into the DT		X	
13	(Abdeen, Shirowzhan, and Sepasgozar 2023) [93]	Citizen-centric digital twin development with machine learning and interfaces for maintaining urban infrastructure	Citizen-Centric DTs		X *	X
14	(Yossef Ravid and Aharon-Gutman 2023) [75]	The Social Digital Twin: The Social Turn in the Field of Smart Cities	Physical and Social Integration of DTs in City Planning			X
15	(Liu et al. 2023) [78]	Towards Human-centric Digital Twins: Leveraging Computer Vision and Graph Models to Predict Outdoor Comfort	Human-Centric DTs		X	
16	(Ye et al. 2023) [41]	Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda	Human-Centered UDTs		X	

Table 1. Cont.

No.	Authors	Title	Main Focus of Paper	SDT Focus Area		
				Concept and Modeling	Governance and Social Input	Social Applications
17	(Viale Pereira et al. 2023) [94]	Smart Cities and Digital Twins in Lower Austria	Smart City DT Governance and Social Sustainability		X *	X
18	(S. Wang and Vu 2023) [95]	The integration of digital twin and serious game framework for new normal virtual urban exploration and social interaction	DTs and Serious Games for Enhanced Social Interaction		X	X *
19	(Masoumi et al. 2023) [96]	City Digital Twins: their maturity level and differentiation from 3D city models	Maturity of UDT governance		X *	X
20	(Caldarelli et al. 2023) [97]	The role of complexity for digital twins of cities	Sociotechnical Complexity of UDTs	X *	X *	
21	(Al Jurdi, Wehbe, and Mroueh 2023) [98]	Integration of citizens' feelings and feedback into the city information modeling environment	UDTs and Citizen Data		X	
22	(Gkontzis et al. 2024) [99]	Enhancing Urban Resilience: Smart City Data Analyses, Forecasts, and Digital Twin Techniques at the Neighborhood Level	UDTs and Citizen Data for Analytics and Prediction		X *	X
23	(Batty 2024) [9]	Digital twins in city planning	Physical and Social Integration of DTs in City Planning		X *	X
24	(Lei, Liang, and Biljecki 2024) [5]	Integrating human perception in 3D city models and urban digital twins	Integrating Human Perception into UDTs		X	
25	(Lei, Su, and Biljecki 2024) [100]	Humans As Sensors in Urban Digital Twins	Integrating Human Sensing Data into UDTs		X	
26	(Haraguchi, Funahashi, and Biljecki 2024) [101]	Assessing governance implications of city digital twin technology: A maturity model approach	Maturity of UDT governance		X *	X
27	(Shan et al. 2024) [102]	Influencing factors and action paths for public crisis governance performance improvement in digital twin cities	Public Crisis Governance using UDTs	X	X *	

Table 1. Cont.

No.	Authors	Title	Main Focus of Paper	SDT Focus Area		
				Concept and Modeling	Governance and Social Input	Social Applications
28	(Chukhno et al. 2024) [103]	Learning-powered migration of social digital twins at the network edge	SDTs Paired with Social IoT (SIoT)	X		
29	(Netto Emmanouilidis, and Khargonekar 2024) [104]	Systems and Control for Societal Impact: IFAC TC 9.2 Visions and UN SDGs	Sociotechnical DTs	X *		X
30	(Park et al. 2024) [105]	“DigitalMe” in smart cities	Smart City DTs for Healthcare Planning	X		X

Research in the SDT field is still in its nascent stages, with many areas remaining underexplored. However, there is a growing interest from researchers across various disciplines, reflecting a promising trajectory for future developments. The findings presented in Table 1 indicate that the existing literature on SDTs can broadly be categorized into three primary focus areas, each addressing distinct aspects of the SDT as follows.

3.1.1. Concept and Modeling: Human Twinning in Urban Environments

Researchers often describe SDTs as digital representations of individual humans, capturing aspects of human activities, roles, and knowledge. These digital models aim to advance the UDT concept by focusing on the dynamics of “place” rather than merely “space”. This approach allows for a more rigorous understanding of human needs, capabilities, and limitations in urban environments [4,100]. The twinning process is supported by both direct and indirect measurements of human behavior, creating a bidirectional flow of information between humans and their digital twin that enables real-time updates and synchronization [4,104,106,107]. The intent behind SDTs is to build a theoretical and technical framework for simulating human behavior and interactions in urban settings. This involves creating realistic and actionable socio-technical models that effectively represent individual and collective dynamics while highlighting the unique characteristics of urban “places” [6,7,51–53].

Key applications of SDTs in this area include behavior modeling, such as activity simulation (e.g., running, walking), and social interaction modeling, which reflects how individuals interact both digitally and in the physical world. These interactions form a dynamic feedback loop, enabling SDTs to adapt based on real-world experiences [9,77,102]. Additionally, some studies have explored modeling interpersonal relationships (e.g., friendships, family ties) and broader social relations (e.g., ethics, morality, law) in the digital twin model [92].

In more advanced iterations, SDTs evolve into digital selves, where digital twins are enriched with socio-cognitive capabilities. This includes the ability to understand and replicate social and emotional responses, making them more interactive and socially aware in their interactions with humans and systems [91,97]. Over time, by learning from human interactions, behaviors, knowledge, and experiences, SDTs can support decision-making and refine models [4,100].

The overarching objective of this research direction is to develop robust, data-driven models that serve as the conceptual backbone of SDTs. This includes integrating human

behavior, social interactions, and community dynamics to improve representation, management, and prediction of social components in UDT models [89].

3.1.2. Governance and Social Input: Human Participation in UDT Development

SDTs are designed to capture and digitally represent human knowledge and behavior of the “place” by adding subjective human experiences into UDT models. This inclusion enhances the representation of social dimensions, improving decision-making processes and supporting a range of urban applications [100]. Therefore, the governance approach adopted is essential for ensuring these models accurately incorporate human input and genuinely reflect the needs and interests of urban populations [66]. Citizen participation is increasingly recognized as a fundamental component in the governance of smart cities, enabling a more democratic and community-centric approach to urban development [108].

Governance in SDTs involves urban planners, policymakers, developers, and citizens collaborating to shape public policies and services [109]. Through e-governance models, which prioritize digital platforms, citizens can actively participate, ensuring their needs and preferences influence projects. SDTs in this area act as interactive platforms that communicate community concerns and preferences, facilitating decisions that align with public expectations [41,88,95,110–112].

Citizen engagement in smart city UDTs varies significantly, influencing how residents contribute to urban governance, sustainability efforts, and the co-creation of solutions [60,101]. Defining desired outcomes of citizen participation is crucial, with various models outlining different levels of involvement [55,113].

At the basic level, information sharing involves decision-makers disseminating project details to citizens without seeking input, resulting in one-way communication. Progressing further, citizens may act as data sensors, providing information through digital tools, although their preferences are not incorporated into decision-making. A more inclusive level involves sharing citizen experiences and knowledge, where decision-makers integrate citizens’ preferences indirectly. The highest level is active participation, where citizens collaborate directly with governments and stakeholders, shaping urban development and decision-making processes [55,113].

As citizen participation progresses toward more active participation, it transitions from a top-down approach to a bottom-up model, where residents play a crucial role in shaping the decisions that affect their lives and communities, as shown in Figure 7. Effective citizen participation requires that citizens are genuinely heard and their opinions considered in decision-making. This active engagement is essential for the success of UDT projects, as it fosters a sense of ownership and responsiveness to the community’s needs.

A key feature of SDTs is their ability to facilitate interaction between digital models, humans, and external systems. This capability allows SDTs to act autonomously in providing real-time information and feedback [4]. As an example, the CITYSTEPS maturity model, proposed in [101], illustrates the governance and development of UDT through an eight-stage framework, from initial planning to real-time synchronization and autonomous decision-making, emphasizing human involvement. It highlights UDTs’ potential to enhance transparency, accountability, and inclusion while addressing challenges like privacy and social exclusion [101]. Therefore, SDTs can be viewed as tools that enable citizens, local authorities, and institutions to collaborate, visualize, and influence urban decisions in real time [9,63,86,89,94,96,97,100,111].

Human-centric digital twins (HCDTs), which can be considered a part of the SDT concept, are increasingly popular for achieving effective bottom-up governance in various UDT projects within the framework of SDTs. HCDTs are designed with citizens as core contributors through all stages, recognizing that, as frequent users of urban landscapes, they

are well positioned to identify relevant issues and contribute significantly to maintaining and improving city ecosystems. They directly integrate human and social dynamics into the UDT model, aligning with the core principles of SDTs [9,75,77,78,88,89,96,111]. Human interaction is key in shaping and utilizing these UDTs, with planners, scientists, and citizens interacting with the twin to model, monitor, and predict urban and social behaviors [41,88,97,102,112]. The SDT concept is further realized through technologies that enable the collection of citizen feedback, which is then integrated into urban governance. Citizens can report issues such as waste management problems, infrastructure failures, or social challenges, ensuring that the UDT reflects not only physical infrastructure but also social interactions, preferences, and behaviors [93,95].

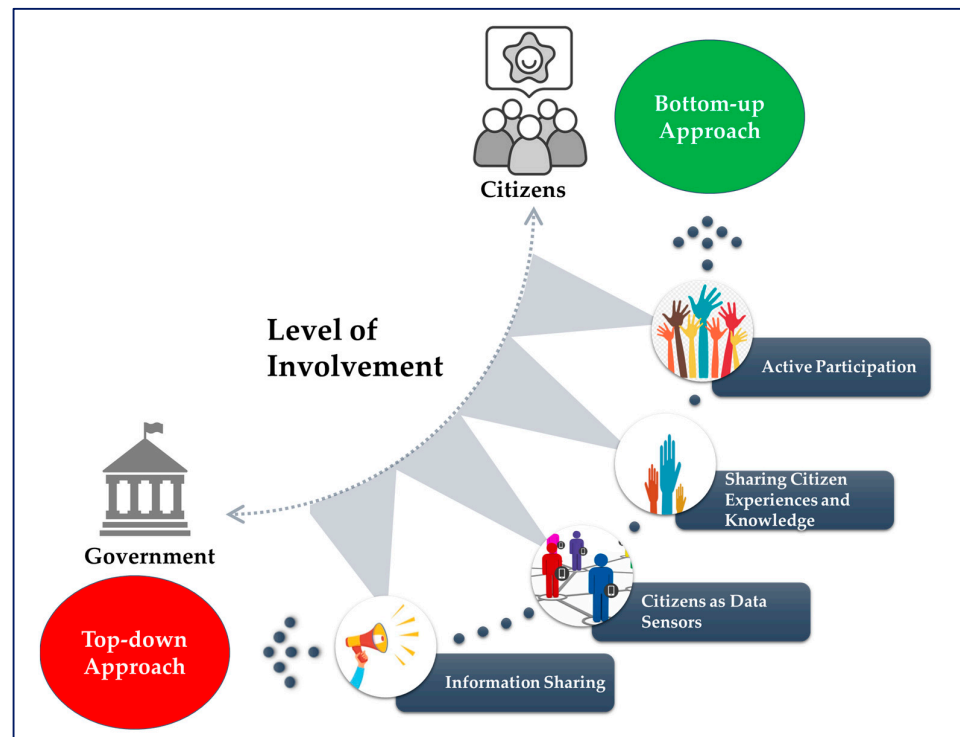


Figure 7. The governance approach and levels of citizen involvement in smart city UDT projects.

The SDTs mark a significant shift from the dominating top-down approaches, where citizen engagement typically occurs after the design phase. Instead, SDTs integrate community feedback directly into the entire process of system development [93,96,100]. Thus, SDTs enable more transparent, participatory governance, allowing citizens to interact with and influence urban planning while addressing critical issues such as privacy, transparency, and accountability. This participatory model strengthens the relationship between system development and the needs of its residents, making cities more responsive and equitable. It also improves the accuracy and quality of social component modeling in the SDT model, ensuring a more authentic representation of the “place” [41,89,94,101,102].

3.1.3. Social Applications: Addressing Social Issues Using UDT

UDT applications typically focus on using the technology to improve urban living conditions, focusing on efficient transportation, energy management, and enhanced communication systems [38,64,114–116]. However, these technical solutions often overlook intangible social aspects related to the “place” like historical context, cultural values, and the social needs of communities. In response, this approach of SDTs leverages DT technology to address residents’ authentic needs, emphasizing social challenges and fostering a holistic, community-oriented perspective in the system development.

Increasingly, UDTs are being applied to social systems. In the context of city planning, SDTs extend beyond the physical infrastructure to focus on the behavioral and social processes that shape urban environments [9,75,85]. The SDT concept is particularly useful for addressing uncertainty, diversity, and complexity in societal challenges. By simulating human psychological and behavioral responses, SDTs offer more agile and targeted approaches to managing real-world social issues. Built on the foundations of social computing and computational social sciences, SDTs can digitally model social problems and phenomena [75,85,117]. By integrating dynamic human mobility and social data, SDTs provide real-time insights that aid decision-making, enabling the simulation and prediction of social interactions and behaviors in urban settings [101].

These applications are valuable for addressing urban challenges like gentrification, social inequality, aging populations, public health, mobility, and overall quality of life [42,75,112]. For instance, they can monitor changes in neighborhood demographics, understand disparities in access to resources, and design age-friendly infrastructure for older residents [75,89]. Additionally, SDTs can simulate health crises, optimize transportation systems, and foster inclusive, sustainable urban environments [99,105].

3.2. Key Features of SDTs

The key features of SDTs align closely with the main categories discussed in the previous section. This section highlights these features and their progression, starting with enhanced modeling capabilities, including the representation, simulation, optimization, and prediction of social interactions within socio-technical systems. It then addresses the social characteristics of SDTs, highlighting their role in promoting inclusive governance and supporting effective decision-making processes. Lastly, the section broadens the SDT applications, situating them within the larger framework of UDTs and their application in interconnected, complex urban environments.

3.2.1. Advancing SDT Modeling, Management, and Prediction Systems

(1) Theory exploration and social dynamics

One of the defining characteristics of SDTs is their use in theory exploration and explanation. They provide a framework for testing and validating sociotechnical theories by simulating social behaviors and technical system interactions. Several key theories guide SDT development, such as the Broken Windows Theory, which focuses on addressing minor social issues early, and Heinrich's Law, which identifies potential social threats. The Small-World Phenomenon helps explain human connectivity, while Herd Behavior models collective human actions [47,92]. Space Syntax Theory examines the influence of spatial configurations on social dynamics [118–121]. These theories differentiate SDTs from traditional UDTs, which focus more on real-time monitoring and control, by allowing deeper insights through modeling, simulating, and predicting complex relationships between social behaviors and physical systems. This sociotechnical perspective allows SDTs to explore and anticipate the nuances of human–physical interactions within urban and societal contexts.

(2) Dynamic interaction and real-time adaptation

Another defining feature of SDTs is their ability to dynamically interact and adapt to real-world social changes in real time. By continuously updating their models based on live inputs from different sources like social actors, SDTs remain responsive and evolving, ensuring they stay relevant to current conditions. This real-time adaptation improves system efficiency in contexts like urban planning and social feedback loops [63,104]. Also, one of the core advantages of SDTs is their ability to learn and adapt based on past interactions with human systems [4,41,91]. By analyzing patterns in social behavior and

feedback, SDTs continuously improve their responses, ensuring better long-term planning and system performance. However, because human behaviors can be unpredictable, SDTs may require manual updates in some cases rather than relying solely on full automation [47,105]. This flexibility ensures that SDTs remain accurate despite the complexities of human social behavior.

(3) Multimodal social data integration

To build detailed and dynamic models of individuals and communities, SDTs integrate multimodal social data from diverse sources. These data include physiological metrics, such as heart rate and blood pressure, and demographic attributes, like height, weight, age, and temperature, for human representation, as well as data on social interactions and human–environment interactions within urban contexts [77,101,102]. SDTs capture how people engage with the physical systems of the built environment, including preferences and habits in using buildings, public transportation, and urban services. These models consider how various factors influence behavior to gain insight into underlying motivations. By synthesizing these diverse data streams, SDTs can simulate a broad spectrum of human behaviors and environmental interactions, achieving a more comprehensive representation of individuals and communities within urban systems.

3.2.2. Enhancing Social Characteristics Through an Inclusive Governance Approach

(1) Interactive stakeholder participation and autonomous decision-making

SDTs allow for digital and physical interactivity, enabling real-time interaction between humans, external systems, and UDTs. This interactivity supports autonomous feedback, where SDTs provide insights or automate tasks, reducing the need for human intervention and enhancing operational efficiency [4,90,101,104]. Additionally, SDTs foster active stakeholder participation by making the system more interactive and responsive to social inputs. This feature ensures that SDTs support transparent and inclusive decision-making, allowing policymakers and planners to simulate scenarios and consider diverse social, economic, and environmental factors. SDTs play a key role in urban planning by visualizing potential outcomes, enabling more balanced and informed decisions [63,89,98,99,101,110].

(2) Promoting sustainability and social well-being

SDTs also contribute to urban sustainability and social well-being by optimizing resource management and urban planning efforts [94,96,122,123]. By incorporating social data into the design and management of urban environments, SDTs help policymakers create more sustainable, equitable, and livable cities. Their application in assessing smart city policies fosters social cohesion and promotes the welfare of both urban and non-urban communities.

3.2.3. Expanding Accurate and Interconnected Applications

(1) Partial representation for manageable scope

Unlike traditional DTs that aim for a comprehensive model of entire systems, SDT applications usually focus on partial representation within a hierarchical structure. They prioritize specific, critical aspects of social–technical interactions rather than attempting to replicate all system components [47,124,125]. This narrowed scope enables more manageable and precise modeling, which allows for greater concentration on the essential processes and interactions.

(2) Integration within complex and interconnected systems

Although SDT applications are initially designed with a partial representation, these specialized models can be integrated into a larger, comprehensive system application that

incorporates physical, digital, and social components. Within these complex environments, SDTs interact dynamically with other systems, each fulfilling a distinct role that collectively supports a holistic UDT perspective [9,47]. This integrated approach enhances overall system performance, allowing SDTs to contribute meaningfully to networked structures such as smart cities, where they help in optimizing and coordinating various interconnected systems.

3.3. SDT-Related Tools

3.3.1. Foundational Tools and Key Technologies

These core technologies form the backbone of SDT systems, enabling their development, integration, and operation. Primarily of interest to technology developers and industry practitioners, these tools focus on building the necessary infrastructure, facilitating efficient data acquisition, and ensuring robust data processing capabilities.

(1) Architecture, Surveying, and Mapping Technologies

SDTs are supported by an architecture that integrates multiple technologies such as 3D city models, Building Information Modeling (BIM), and City Information Modeling (CIM) [93,98]. These are combined with surveying and mapping technologies to process and visualize urban data, enabling the delivery of integrated holographic data in real-time [61]. These technologies form the foundation for spatially presenting SDT outcomes, enabling diverse stakeholders to visualize, interact with, and interpret complex data in a meaningful way by integrating additional visualization technologies.

Surveying technology in cities involves two main aspects: surveying the city's topography, environment, and spatial structure and mapping this information into an integrated system based on a Geographic Information System (GIS). In surveying, the focus is on four key technologies: tilt photography, Unmanned Aerial Vehicles (UAVs), 3D laser scanning, and Global Positioning System (GPSs) [126,127].

Mapping concentrates on two main technologies: real-world 3D reconstruction and multisource geographic data processing [61]. Recent advancements in tilt photography and UAV technology have significantly streamlined the acquisition of local ortho, tilt, or Lidar point cloud data, reducing the need for extensive field mapping [127]. Three-dimensional laser scanning, employing a high-speed measurement method, accumulates large-area dense point cloud data, facilitating the creation of 3D models and various map data promptly [128].

(2) Social Sensing Technologies (Crowdsourcing and IoT)

Social sensing technologies in SDTs enable the collection and processing of real-time, crowdsourced data to better understand social interactions and behaviors. Volunteered Geographic Information (VGI) integrates data from citizens' interactions with their spatial environment, while social media platforms provide insights through posts, interactions, and location-based check-ins, revealing patterns in public sentiment, mobility, and engagement [93,98,104]. These tools are complemented by the Social Internet of Things (SIoT), where networks of IoT devices mimic human social relationships to gather and share real-time data from social environments [90,103,129]. SDTs serve as intermediaries that facilitate communication among these devices and ensure the integration of social data from diverse sources such as open-data repositories, public records, government databases, and urban statistics.

(3) Edge Computing and Beyond-5G/6G Networks

To ensure real-time processing and low-latency communication, SDTs are often deployed on edge computing platforms [87,90,102,103]. By placing SDTs closer to data sources

such as IoT devices, social media feeds, and public records, edge computing reduces the time it takes for the digital twin to process data and provide feedback, making it more responsive to real-world changes.

Additionally, as beyond-5G (B5G) and -6G networks emerge, SDTs benefit from the enhanced capacity to manage massive volumes of data from interconnected devices. These networks support real-time data processing, enabling SDTs to scale up and handle complex applications like autonomous transportation, smart city management, and Extended Reality (XR) experiences. Integration with open data, public records, and social data will be important in leveraging these networks for real-time urban management [90,102,103].

3.3.2. Specialized Analytical Tools

These tools are used to model and analyze data, providing meaningful insights and accurate predictions to understand and address social dynamics within specific SDT applications. Academic researchers use these tools to further their studies, while policymakers and urban planners rely on them for evidence-based decision-making and shaping informed policies.

(1) Agent-Based Modeling (ABM)

Agent-Based Modeling (ABM) is one of the significant analytical tools used for SDTs, and is particularly suited to capturing the emergent behavior of human agents within sociotechnical systems. ABM simulates individual and group behaviors, offering realistic insights into modeling how people interact with and influence the system [47,110,130–133]. ABM goes beyond traditional approaches, which often oversimplify human behavior, making it ideal for complex social dynamics.

(2) Machine Learning and Artificial Intelligence (AI)

Machine learning and AI algorithms play a critical role in processing the vast amounts of data generated by citizens and IoT devices [93,104]. These algorithms enable the creation of a feedback loop, where social data are continuously updated, allowing SDTs to evolve in real time. By analyzing data from social media, public records, and open datasets, machine learning models can identify patterns and trends, helping improve urban decision-making and planning processes [93,134].

Moreover, advanced AI techniques, such as GraphSAGE-LSTM, further enrich SDTs by modeling and predicting the dynamic relationships between individuals and their environment [26]. For example, these techniques can analyze factors like visual ambiance, sound, pedestrian traffic, and social interactions to predict social dynamics [5,101,135–137]. Furthermore, SDTs use sophisticated algorithms to correlate various social data points, such as loneliness, disability, and other indicators, with geographical features [75]. Thus, SDTs can provide deep insights into the social fabric of different communities, helping city planners and policymakers address specific social needs [78].

(3) Interactive Visualization and Citizen Engagement

Interactive visualization tools and APIs play a key role in engaging citizens with SDTs. Platforms like WebGL and Cesium enable users to visualize 3D models of their cities, allowing them to see how their inputs affect urban infrastructure in real time [93,95,98]. This transparency fosters greater trust and participation from citizens, who can also see how open data or public records inform the planning process.

SDTs are increasingly integrated into metaverse platforms, where digital replicas of cities allow citizens to interact with urban spaces in a fully immersive environment [73,92]. This technology enables users to provide feedback on urban projects by simulating scenarios within a virtual version of their city [138,139]. Social media and public records are often

incorporated to inform these virtual models, creating a more engaging and realistic representation of city life. Moreover, Extended Reality (XR) technologies, such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), are set to revolutionize public participation by enabling citizens to visualize, navigate, and interact with urban plans in immersive, three-dimensional spaces [140,141].

4. Gaps and Challenges in SDTs

While SDTs offer powerful capabilities for modeling human and social behaviors in complex systems, several research gaps and practical challenges persist. Research gaps highlight areas requiring further exploration by academic researchers. Practical challenges, on the other hand, focus on issues arising in real-world implementation. Governments and decision-makers should take the lead in building frameworks to address these practical challenges, collaborating closely with technology developers to provide innovative technical solutions and ensure effective deployment.

4.1. Research Gaps

4.1.1. Difficulties in Modeling Social Components and Human Behavior

There is an inherent gap in SDT research in regard to replicating complex human behaviors and social constructs such as ethics, morality, love, and family dynamics. Mapping these deeply human experiences into the digital realm remains problematic, as the models often struggle to capture the nuanced relationships and emotions between people [47]. For example, while SDTs may mirror interpersonal relationships in digital spaces like the metaverse, translating emotional bonds such as friendship or familial love is far more complicated [92]. In addition, while sensors can track movement patterns and certain social behaviors, they are limited in their ability to infer the underlying motivations or contextual factors influencing these behaviors [47,142,143].

4.1.2. Limited Predictability of Social Dynamics

Another research gap lies in the long-term predictability of social behavior. While cities may seem predictable in the short term, with populations engaging in routinized activities, many social processes are difficult to forecast in most cases. Current social predictions rarely extend beyond a few days, limiting the long-term applicability of SDTs in dynamic urban environments [9,143].

4.1.3. Data Integration Issues

Integrating diverse data sources into comprehensive SDT models is both a critical research gap and a practical challenge. Current research methodologies face challenges in handling the complexity of combining heterogeneous datasets that originate from varied sources, such as governmental agencies, private organizations, and social platforms, within the physical environment. Key research issues include the lack of universal interoperability standards, difficulties in processing real-time dynamic spatial and social data, and inadequate consideration of local sociopolitical or cultural contexts [86,144].

4.2. Practical Challenges

4.2.1. Top-Down Governance and Lack of Citizen Participation

A major practical challenge lies in the top-down governance approach commonly seen in UDT implementation. Current governance models often exclude citizens and some stakeholders from decision-making processes, leading to a lack of trust and transparency. This disconnect can result in poor public-private collaboration, limited social inclusion, and issues related to inequality and injustice [94]. Instead of engaging citizens as active participants in the development and goal-setting of SDTs, they are often reduced to "human

sensors” rather than collaborators [86]. Practical solutions should prioritize participatory approaches that actively involve citizens in shaping SDT goals, fostering social cohesion, and supporting equitable governance.

4.2.2. Ethics and Privacy Concerns

One of the most pressing challenges with SDTs is ensuring data privacy, ownership, and ethical management [77]. With their reliance on human-centric data, concerns arise over how personal information is collected, stored, and shared [145,146]. Risks include privacy breaches, lack of transparency, and inadequate consent mechanisms [146]. Addressing these requires frameworks that enforce transparency, accountability, and user consent. Adopting privacy-preserving technologies (e.g., federated learning, differential privacy), secure data storage, and raising public awareness of data rights can help [145,147,148]. Ethical guidelines must also evolve with technological advancements to protect societal values [146].

4.2.3. Data Quality and Integration Issues

Ensuring high data quality is a significant challenge in implementing SDTs, as biased, incomplete, fake, or unreliable data can undermine their accuracy and effectiveness [75,144]. Social data often carry biases from disparities in collection methods, sample representation, or cultural assumptions, leading to skewed outputs that exacerbate social inequities. Many datasets also lack proper validation, increasing errors and inconsistencies, particularly in resource-constrained environments with underdeveloped open-data frameworks [149,150]. In addition, data integration also has practical challenges that include mismatched datasets, siloed systems, lack of standards, and resource demands, all impacting SDT functionality in practice [144].

Addressing these issues requires standardized data collection methodologies to reduce biases and improve representation [151]. Advanced validation tools, such as machine-learning-based systems for anomaly detection, can enhance data reliability [152,153]. Collaborative open-data-sharing initiatives among governments, private organizations, and communities are essential, especially in underserved places [154–156].

4.2.4. Challenges with Digital Universalism

The concept of digital universalism—the belief that digital models can represent diverse, localized urban realities—faces criticism in SDT development [86]. This approach risks oversimplifying urban complexities, particularly the social and political dynamics that vary from one locale to another. SDTs must be designed to reflect localized needs and avoid the assumption that one model fits all urban scenarios.

4.2.5. Open Data and Accessibility

SDTs use interactive tools to enhance citizen participation and informed decision-making. However, the effectiveness of these tools is often hindered by challenges related to open-data accessibility [75,86]. The limited availability of reliable and open data can restrict the ability of SDTs to deliver meaningful insights, especially in communities where data-sharing frameworks are underdeveloped. In addition, barriers such as a lack of trust in technology, insufficient user training, and general reluctance to engage with digital platforms contribute to low adoption rates [126,157]. This issue is particularly pronounced in marginalized communities, where technological literacy remains low, and access to resources for training and support is limited. Addressing these issues requires targeted efforts to promote digital literacy and inclusive access to technology.

5. Proposed Framework for SDT

To unlock the full potential of SDTs and address the existing research gaps and practical challenges, we propose a comprehensive framework that integrates social dimensions into UDT systems. This inclusive SDT approach prioritizes the representation of “place” over abstract “space”, establishing a foundational step toward the development of more robust SDT systems. By addressing key sociotechnical issues, this framework serves as a flexible and adaptable foundation, offering value to researchers interested in applying or building upon this framework for broader applications. The proposed framework is designed to operate in a structured manner, progressing through four key stages: conceptualization, data transmission, modeling, and application of SDTs. It balances technical, social, and governance dimensions to ensure a holistic approach to SDT implementation (see Figure 8).

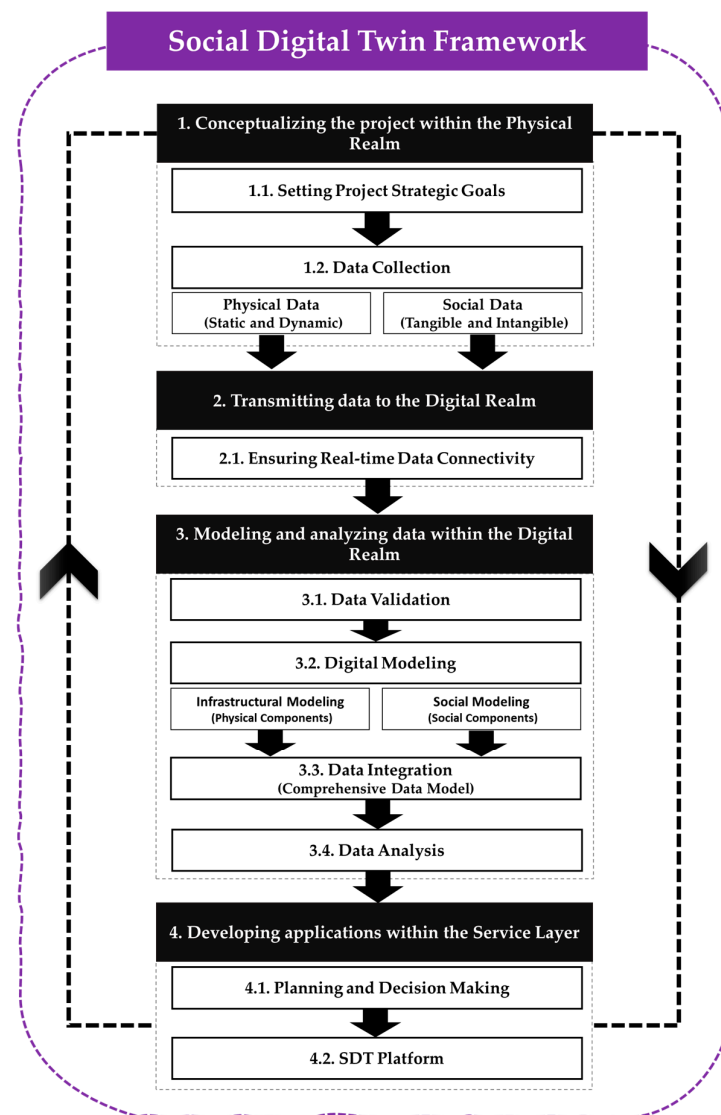


Figure 8. Proposed SDT framework.

5.1. Conceptualizing the Project Within the Physical Realm

5.1.1. Setting Strategic Project Goals

The conceptualization process starts in the physical realm, as it begins with defining project goals and strategic objectives, which serve as the foundation for subsequent steps. A participatory approach is employed to ensure alignment with the genuine needs of citizens and all stakeholders. Once goals are set, the framework defines and examines various UDT

components to fulfill these objectives. These components include physical systems such as infrastructure and buildings, the physical environment encompassing different systems, natural landscapes and geographic features, physical processes involving dynamic urban activities, and human behavior and interactions with both the physical systems and each other (geo-individuals and geo-socials). The goal is to capture the full complexity of “place” within the urban environment, considering both its physical and social dimensions.

5.1.2. Data Collection

Data collection is an important phase in developing SDTs, including both physical and social dimensions. Physical data collection involves a combination of static and dynamic data, gathered using a range of advanced technologies tailored to specific components of urban systems. Surveying and mapping tools, such as tilt photography, UAVs, 3D laser scanning, GPS, real-world 3D reconstruction, and multisource geographic data processing, are employed to capture the physical characteristics of the environment. Additionally, IoT technologies play a critical role in collecting real-time data on physical processes, enabling the creation of accurate, dynamic models of urban systems.

Social data collection, on the other hand, focuses on capturing both tangible and intangible aspects of human interactions and behaviors. SIoT technologies are particularly effective for monitoring dynamic activities in urban spaces, utilizing behavioral and performance indicators. A participatory, bottom-up approach is essential for accurately representing the social dimensions of the urban environment. Data on social behavior are sourced from social media, public records, VGI, and direct citizen contributions to ensure inclusivity and relevance.

By integrating these diverse data sources and fostering active citizen engagement, SDTs can comprehensively capture both physical and social aspects of urban “places”, providing a holistic and detailed view of the city.

5.2. *Transmitting Data to the Digital Realm*

The connection layer plays a critical role in ensuring the SDT accurately reflects real-world conditions by maintaining a continuous, real-time data connection. This step enhances responsiveness, allowing the SDT to adapt quickly to changes in the urban environment. The primary objective of the connection layer is to facilitate the transmission of data between various sources in the physical realm, such as IoT sensors and municipal databases, and the digital realm. This is achieved through a bidirectional data flow, ensuring timely and accurate updates.

To enable efficient real-time data transmission, various communication protocols can be employed. These include LoRaWAN (Long-Range Wide-Area Network), which supports low-power, long-range communication; Message-Queueing Telemetry Transport (MQTT), a lightweight protocol ideal for IoT device communication; and Hypertext Transfer Protocol (HTTP), which ensures reliable data transmission over the web. These protocols collectively ensure that data from multiple sources are transmitted in real time, allowing the SDT to continuously update and maintain an accurate representation of urban conditions.

5.3. *Modeling and Analyzing Data Within the Digital Realm*

5.3.1. Data Validation

The first step in the modeling process is the validation of data collected from various sources. This process ensures the reliability and accuracy of inputs, particularly those contributed by citizens, while addressing potential challenges such as inaccuracies, biases, or false information. Effective validation mechanisms should be implemented to filter and verify data, thereby ensuring the integrity of the SDT’s data infrastructure.

5.3.2. Digital Modeling

The digital modeling phase comprises two key components: infrastructural modeling of physical elements and social modeling of dynamic social interactions.

Infrastructural modeling focuses on developing a comprehensive UDT to represent physical entities like buildings, roads, and utilities, using tools such as GIS, BIM, tilt photography, UAVs, and 3D laser scanning. These technologies streamline data acquisition and enable rapid 3D model creation, while integrating physical data attributes, behaviors, and relationships for urban planning and management that are collected by IOT technologies.

Social modeling enhances the UDT by evolving it into an SDT, incorporating social components such as stakeholder relationships, processes, and simulated interactions. This transformation shifts the model's focus from representing mere "space" to embodying a dynamic "place". This phase emphasizes participatory input, ensuring stakeholders actively contribute insights that enrich the model. Privacy protections and autonomous data collection methods are critical to safeguarding sensitive information. To enhance the modeling, analysis, and prediction of social dynamics, hybrid social modeling methods are employed. Two key methodologies—Space Syntax and Agent-Based Modeling (ABM)—are integrated to achieve this. Space Syntax analyzes how the physical layout of urban spaces influences social behaviors, while ABM simulates interactions between individuals in these environments over time. These methodologies, supported by purpose-driven SDTs, enable robust modeling and simulation of social behaviors, providing significant insights for planning, scenario testing, and decision-making.

By effectively combining infrastructural and social modeling with careful data stewardship and active stakeholder engagement, the digital modeling phase delivers a secure, inclusive, and comprehensive representation of a city's physical and social dimensions.

5.3.3. Data Integration

Once validated and modeled, the data are integrated into a comprehensive data model, which is managed within the digital realm. The process of effective data integration consists of several stages. First, data from multiple sources are aggregated into a unified platform. Then, these data undergo cleaning and preprocessing to ensure accuracy and usability. Following this, the integration of model data takes place, which includes incorporating 3D spatial geometric models and IoT sensor data through the Industry Foundation Classes (IFC) concept, alongside human and social input [1,158–160].

Efficient storage and management of data are critical for handling large datasets and ensuring rapid data retrieval. This involves a strategic combination of databases and cloud storage solutions to address the varying needs of structured, semi-structured, and unstructured data within the SDT environment [119,161,162]. Beyond storage, maintaining data quality and ensuring robust security measures are paramount to preserving the reliability, trustworthiness, and overall functionality of the system [154,163–166].

5.3.4. Data Analysis

The data analysis phase follows the development of a comprehensive data model and begins with defining purposive SDTs. This step requires a clear understanding of the system's scope, components, operational scale, technological complexity, and involved stakeholder roles. SDTs replicate the physical city in a digital environment, integrating 3D models, multilayered data, and social insights tailored to fields such as transportation, energy, and housing. These models incorporate spatial, social, and attribute data to simulate interactions within the built environment while capturing social dynamics.

Human participation ensures accurate representation of social aspects, aligning the system with stakeholder preferences. The analysis focuses on diagnosing current conditions,

identifying trends, and informing future predictions across economic, environmental, and social dimensions. Key data types—spatial, social, and governance—are processed to deliver insights through a visualization platform, where stakeholders review results and provide feedback. This iterative process optimizes decision-making and adapts the system to evolving needs.

5.4. *Developing Applications Within the Service Layer*

5.4.1. Planning and Decision-Making

The planning phase integrates input from the analysis phase, allowing governments and urban planners to better understand and predict unmeasurable indicators from the physical world's past, thus offering a more comprehensive assessment of urban dynamics. SDTs enhance decision-making through real-time monitoring, simulation, scenario analysis, predictive and prescriptive analytics, and public engagement. They also facilitate performance monitoring and continuous improvement by providing collaborative tools for more efficient urban planning and optimization. Technologies such as AI and machine learning are crucial for effective analysis and planning, as AI-based systems continuously learn from social inputs to improve decision-making in various urban contexts. The results from the planning phase are visualized within the SDT platform for stakeholder feedback, which then serve as input for the decision-making process.

Additionally, the decision-making phase is a critical step in the SDT framework, as it enables more structured, data-driven governance and facilitates citizen participation in decision-making processes. The SDT functions as a key tool for improving urban governance, allowing decision-makers and citizens to engage in monitoring and assessing government actions. Structured methodologies such as Decision Support Frameworks (DSFs) help navigate complex urban decisions. Techniques like Multi-Criteria Decision Analysis (MCDA) and decision trees offer systematic approaches to evaluate multiple criteria and visualize decision pathways [167,168]. These methodologies are integrated into SDT platforms, enhancing stakeholder collaboration and streamlining decision-making.

By linking the decision-making layer with the SDT platform and human participation, a more participatory and bottom-up decision-making system is created. This system allows for continuous feedback from citizens and stakeholders, ensuring that urban governance is responsive to real-time data and social input. Additionally, this feedback mechanism enables alerts and responses from the digital to the physical realm, helping to address specific problems or improve current and future conditions, whether in the context of planning or decision-making. Feedback can be delivered either manually or through automated systems, depending on the system's level of maturity and development.

5.4.2. SDT Platform (Data Visualization)

The data visualization phase is essential for transforming the modeled entities and data of the SDT into clear, actionable visual formats. This step ensures that the SDT becomes accessible and valuable to stakeholders [169]. The primary goal is to develop interactive and intuitive visualizations that effectively present data and model outcomes in an open format, ensuring transparency. This allows stakeholders to view and provide feedback on the data, with different levels of access based on data sensitivity and regulatory requirements [170].

Visualization tools and platforms include user interfaces, dashboards, and visual tools that support data analysis, decision-making, and the communication of complex information [171]. A variety of technologies can be used, such as GISs for interactive maps and spatial analytics, Business Intelligence (BI) tools for developing dashboards and reports, and 3D modeling tools for creating detailed 3D simulations. Additionally, web and mobile development frameworks support the creation of interactive, responsive interfaces.

Each layer within the SDT is linked to the visualization platform, allowing users to interact with the system and contribute insights, thereby fostering a dynamic, participatory SDT ecosystem through a feedback loop.

5.4.3. Scalability and Applicability

To address scalability and applicability across diverse urban contexts, including in under-resourced cities, the proposed SDT framework incorporates adaptive components designed for flexibility based on available resources and infrastructure. For example, it emphasizes leveraging low-cost IoT technologies, open-source tools, and community-driven data collection methods to ensure accessibility while maintaining data quality. The framework also supports a hybrid approach, combining manual and automated methods depending on resource availability. Furthermore, it considers governance issues, offering strategies to address challenges such as limited data availability, data quality, accessibility, and digital literacy gaps, thereby enhancing its relevance across varied environments.

5.5. Proposed SDT Governance Model

The governance model proposed for the SDT framework emphasizes effective inclusivity by employing a bottom-up approach to ensure greater participation and fairness in urban processes. Central to this model is the engagement of key stakeholders, including the project team, governmental authorities, and the general public, whose roles and responsibilities are diverse but collaborative through the SDT platform. The framework supports an environment where public participation is prioritized, creating more opportunities for citizens to contribute meaningfully to the system.

The governance process begins with the project team facilitating collaboration among all stakeholders. From the initial stages, stakeholders—including citizens, governmental authorities, and the project team—collectively set strategic goals and objectives. This collaboration extends to data collection, analysis, planning, and decision-making. Citizens, along with community and private organizations, contribute by supporting the collection and modeling of social data in partnership with the project team. Meanwhile, governmental authorities, in conjunction with the project team, focus on validating data to ensure accuracy and take on more technical tasks such as data integration and infrastructural modeling. Once the project is implemented, these entities work together to take actions to address existing challenges and improve urban systems (Figure 9).

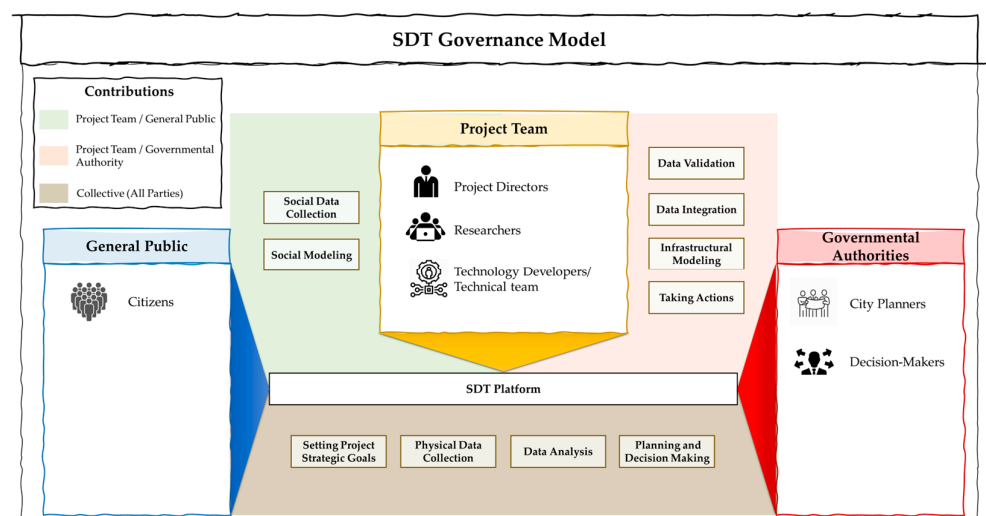


Figure 9. Proposed SDT governance model.

This governance model promotes broader stakeholder engagement while addressing challenges related to social inclusion, inequality, and injustice. Transparency is a fundamental principle, ensuring open access to data for stakeholders to use and build upon through the SDT platform. At the same time, privacy and security measures are prioritized to protect individual information. Data collection processes should be designed to respect privacy, and robust security mechanisms, such as encryption and role-based access controls, safeguard sensitive data [158]. For instance, encrypting real-time data streams from IoT devices ensures their security during transit across networks [171]. Additionally, access controls regulate who can view or manipulate specific data, preventing unauthorized access to sensitive demographic or personal information [170]. These measures not only ensure compliance with regulatory standards but also foster trust among stakeholders involved in the SDT system.

The proposed governance framework adopts a balanced techno-social approach, placing significant emphasis on human input in the SDT process. Human participation and insights play a key role in the stages of SDT development and indirectly shape technology-driven aspects through their integration within the SDT platform. By incorporating human inputs effectively into the digital environment, the framework leverages technology to optimize outcomes while maintaining the centrality of the social dimension.

6. Conclusions

DT technology has advanced significantly in managing urban infrastructures, yet its focus on the physical aspects of “spaces” has constrained its capacity to address the complex social dynamics of “places”. Current UDTs often overlook social dimensions including human behavior, social interactions, and citizen engagement, resulting in a disconnect between technological systems and the lived urban experience. This paper responds to these gaps by advocating for the SDT, a concept that integrates social dimensions into UDT models.

The paper contributes by providing a comprehensive review of the existing literature and proposing a detailed framework with a governance model. SDTs are viewed as dynamic, holistic models of urban environments that designed to replicate social aspects through various stages. These SDTs continuously simulate and integrate city infrastructure, environment, and social dynamics, positioning people as essential components of these systems. The literature on SDTs categorizes the focus into three primary areas, ranging from conceptual development to practical application: (1) conceptualization and modeling, which focus on capturing and digitally replicating human behavior in urban places; (2) human participation and governance, promoting citizen involvement in SDT governance for enhanced decision-making; and (3) social applications, where SDTs serve as tools to tackle social urban challenges, such as social inequality and public health.

SDTs capture the interplay between social and technical systems in real time, enabling city managers to respond effectively to dynamic urban needs. The key features of SDTs include advanced modeling, management, and prediction of social systems, the integration of social characteristics through inclusive governance, and the development of accurate, interconnected applications within complex urban systems. Through the integration of key technologies like architecture and mapping technologies, social sensing via crowdsourcing, and edge computing with Beyond-5G/6G networks, SDTs enable responsive urban management. Specialized analytical tools, including ABM, AI-driven analytics, and interactive visualization platforms, further enhance social systems representation.

Despite their potential, SDTs face several challenges, both in research and practice. Research gaps include difficulties in modeling social components and human behavior, the limited predictability of social dynamics, and issues with data integration due to mis-

matched datasets, siloed systems, and the lack of universal standards. On the practical side, SDTs struggle with top-down governance structures, ethics, and privacy concerns, including privacy breaches and data biases. Data quality and integration issues further hinder effectiveness, while challenges related to digital universalism and limited accessibility for marginalized communities remain significant barriers.

To address research gaps and practical challenges, a comprehensive framework is proposed to integrate social dimensions into UDT systems along with a governance model. This inclusive SDT approach prioritizes the representation of “place” over abstract “space”, laying a foundation for robust and adaptable SDT systems. The framework progresses through four stages, conceptualization, data transmission, modeling, and application, balancing technical, social, and governance considerations. Governance aspects ensure the SDT’s operation within legal and ethical standards, promoting transparency and collaborative governance. By addressing sociotechnical issues, it provides a flexible structure for researchers and ensures a holistic approach to SDT implementation.

Future work will focus on validating the proposed framework through real-world applications, developing specialized SDT solutions for sectors such as transportation and urban planning, and creating structured methodologies to enhance social dynamics representation. Additionally, efforts will focus on refining detailed, lower-level methodologies that foster social inclusivity, enabling broader participation across diverse urban populations. Establishing governance standards to ensure an active, bottom-up approach will be essential, putting citizens and stakeholders at the forefront of the process.

The research limitations of this framework stem primarily from its foundational nature; while it serves as an initial step, it does not yet fully capture the finer-grained social aspects that more specialized applications and subsequent frameworks will need to address. Additionally, limitations related to ethics, privacy, data accessibility, and the inherent complexity of urban social processes remain significant. Political factors present another crucial challenge: if there is tension between citizens and the government, or if citizens distrust the authorities, participation levels may drop, directly impacting the effectiveness of SDTs in reflecting the true social dynamics of urban spaces. The reliance on top-down governance models can further restrict transparency, hinder citizen collaboration, and create data accessibility issues, particularly for marginalized communities. Moreover, issues related to data quality, integration, and standardization will require ongoing refinement to improve the accuracy of SDTs in modeling and predicting complex, long-term social dynamics. Addressing these limitations is essential for advancing SDT systems that are adaptable, socially inclusive, and capable of supporting responsive, human-centered urban environments.

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