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Assessing Governance Implications of City Digital Twin Technology: A Maturity Model Approach

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Highlights

- Our maturity model assesses the different development stages of city digital twins.
- We identify opportunities and impediments to better governance.
- City digital twin technologies can enhance public participation in urban planning.
- The technologies can resolve smart cities' long-standing challenges.
- Challenges remain, including interoperability, participation, and inclusivity concerns.

Abstract

Digital twin technology has great potential to transform urban planning. However, the governance aspects of city-scale digital twins (CDTs)— a virtual representation of urban environments —are understudied. This study bridges this knowledge gap by adopting a framework that scrutinizes the maturity stages of technology. We introduce the CITYSTEPS Maturity Model, a pioneering maturity framework tailored for CDTs, to assess all development stages of CDTs, including those utilizing artificial intelligence, and analyze the technology's role in urban governance. We highlight the promise of CDTs in enhancing public participation in urban planning and addressing key smart city concerns, such as accountability and transparency. However, significant challenges remain, including public participation, public trust in privacy protection, and technical impediments like inadequate data integration, systems integration, and interoperability. There's also the pressing issue of social inclusion: the potential exclusion of marginalized groups, including those often overlooked in data collection, like the hidden homeless and informal sector workers. We propose CDTs should be designed with a human-centric approach, transparent and unbiased data collection and algorithms development, and be led by an adaptive regulatory framework. The CITYSTEPS Maturity Model lays out a framework to assess CDTs' present state, forecast their future, and understand their governance implications, promoting more inclusive technology adoption.

Keywords: city digital twin, maturity model, governance, public participation, inclusion, smart city

Abbreviations used in the study[1]

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[1] City digital twin (CDT).
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Digital Twin and 3D models (DUET)

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1. Introduction

In an age of digital connectivity, the implications of new technologies for cities are more pressing than ever. A digital twin is an emerging technology characterized by "a living virtual model, a connected digital representation of a physical system" (Ketzler et al., 2020). The technology has been widely introduced in various sectors, such as manufacturing (M. Liu, Fang, Dong, & Xu, 2021), building (Harwood & Eaves, 2020), energy (Y. Wang, Kang, & Chen, 2022), climate and earth systems (Voosen, 2020), transportation infrastructure (Klar, Fredriksson, & Angelakis, 2023), and healthcare (Y. Liu et al., 2019). City planning is no exception. Recently, national and local governments, along with big tech companies, have applied the technology to city planning and the built environment, the so-called City-scale Digital Twin (CDT)[2](Ketzler et al., 2020).

CDT is a virtual replication of a city's physical assets, landscape, and human activities, created through the use of data, analytics, and computational techniques. The process of creating a CDT involves encoding semantic and geospatial properties of city objects (Lei, Janssen, Stoter, & Biljecki, 2023). Unlike other digital twins, CDT enables two-way interaction with the physical city, making analytical operations and simulations possible within the virtual environment (Lehtola et al., 2022; Lei, Janssen, et al., 2023). CDT includes not only the built environment but also human activities, making it an essential tool for urban planners to evaluate the impacts of various urban planning interventions and future changes, such as planned construction projects or emergency management during a crisis. With these simulations and impact assessments, decision-makers can assess policy impacts and determine better solutions. CDT can improve

[2] In this paper, CDT is defined as a living virtual city model, a connected digital representation of a physical urban system (Ketzler et al., 2020).

the different aspects of smart cities, such as better urban planning with more involved citizen participation, integrated operation with interoperable systems, and the improved accessibility of data to the public. In practice, national governments (e.g., the United Kingdom, Singapore, Japan), municipal governments (e.g., Zurich, New York, Chattanooga, Shanghai), private companies (e.g., PricewaterhouseCoopers, McKinsey), European Union, and international organizations (e.g., the World Bank) show growing interest in this digital technology.

City planners have high expectations that CDT will help resolve complex issues of smart cities (Hurtado & Gomez, 2021). Smart cities face numerous challenges across governance, social, economic, technological, legal, and ethical domains (Rana et al., 2019), including transparency(Jacobs, Edwards, Markovic, Cottrill, & Salt, 2020), citizen participation (Cardullo & Kitchin, 2019), and accountability issues arising from a lack of citizen-centered data governance (König, 2021). For instance, the lack of citizen participation hinders their ability to envision how smart cities could improve their daily lives (Kogan & Lee, 2014; Komninos, Pallot, & Schaffers, 2013; Schuurman, Baccarne, De Marez, & Mechant, 2012). CDT technology has the potential to enhance citizen involvement in urban planning and implementation by providing visualization features. Conducting an in-depth analysis is crucial to exploring the diverse pathways through which CDT can tackle these challenges across various levels.

At the same time, CDT has its own particular challenges because of the following differences from other digital twin technologies (Nochta, Wan, Schooling, & Parlikad, 2021). First, much of the data feeding for CDT is not readily available or accessible due to dispersed data ownership, a lack of data-sharing schemes, and security and privacy concerns (Nochta et al., 2021). Second, there is a lack of clear value propositions or benefits that could justify the required data collection and sharing across multiple actors (Lei, Janssen, et al., 2023; Nochta et al., 2021). Third, social and economic aspects of how people and social systems should be involved and represented are understudied compared to technological sides (Nochta et al., 2021; Tomko & Winter, 2019). Subsequently, CDT faces unique challenges that other digital twin technologies do not encounter. For example, there are several challenges in governance factors, such as public participation and inclusion. To analyze and address these challenges, we develop a maturity model, a framework that measures the technology level of maturity, such as quality, competency, sophistication, or progress toward goals (Becker, Knackstedt, & Pöppelbuß, 2009; Warnecke, Wittstock, & Teuteberg, 2019).

Specifically, this paper sets out to achieve three objectives. The first is to develop a maturity framework for CDT technologies. Second, using the developed maturity model, we aim to examine how CDTs can address long-standing challenges in smart cities. Finally, we analyze the current impediments to CDT from governance perspectives.

The rest of the paper is organized as follows. In Section 2, we review the current literature on governance and maturity models of CDTs. In Section 3, we delineate our method. In Section 4, we develop a framework of the CDT maturity model that can be used to assess the development status of CDT initiatives. Then, in Section 5, we evaluate the governance perspectives, namely transparency, accountability, participation, and inclusion. Section 6 discusses how CDTs can contribute to the challenges of smart city development. Section 7 argues challenges in technology development, participation, and inclusion. In Section 8, to address these challenges, we discuss policy implications and potential regulatory frameworks. In Section 9, we explore the promises and sustainability of CDTs from the standpoints of scalability and adaptability.

2. Literature review

Governance

Governance plays an instrumental role in the advancement of CDTs within urban planning. Within the CDT framework, governance encompasses several dimensions, namely accountability, transparency, participation, and inclusion (Castelnovo, Misuraca, & Savoldelli, 2016; Waddington, Stevenson, Sonnenfeld, & Gaarder, 2018; Welch, 2012). Previous studies underscore the significance of governance in this discourse. Two predominant themes emerge regarding CDTs:

First is *the governance of CDTs*: how to effectively manage and implement CDT technologies to realize their full potential. This involves protocols, regulations, operability, and, particularly, data governance underpinning CDTs (Vasiliu-Feltes, 2023). Existing research indicates that traditional urban planning issues and those in CDTs intersect. Ellul, Stoter, and Bucher (2022) observe that challenges within geospatial communities and those associated with CDTs converge, particularly in areas like interoperability, data management, and governance. Through stakeholder interviews from various CDT projects, D'Hauwers, Walravens, and Ballon (2021) identify data governance as the fundamental challenge for CDTs. They also assert that the discussion around CDTs mandates a multi-stakeholder engagement approach. Moreover, Klar et al. (2023) emphasize that multistakeholder governance and collaboration constitute one of the three fundamental requirements for constructing a digital twin of a port. As control over data sources and the trajectory of CDTs progresses, governments are envisioned to transition from a passive to a proactive role. Chaudhuri and Anand (2023) underscore that a well-structured policy framework for technology governance is essential to establish a trustworthy smart digital service. Yet, comprehensive studies delineating the governance structure of CDT technology remain sparse. This paper aims to explore governance subcomponents: transparency, accountability, inclusion, and participation.

Second is *the CDTs for urban governance*: Central to this matter is the potential of CDTs to improve urban governance. Studies suggest CDTs are fundamental for governance in urban planning (Corrado, DeLong, Holt, Hua, & Tolk, 2022; Petrova-Antonova & Ilieva, 2019), especially in participatory decision-making (Caprari, Castelli, Montuori, Camardelli, & Malvezzi, 2022) and evidence-based policy-making (Wan, Nochta, & Schooling, 2019). Ludlow, Khan, Chrysoulakis, and Mitraka (2023) emphasize the needs and opportunities presented by utilizing CDTs for decision-making, especially in light of challenges such as climate change and post-COVID-19 lifestyle shifts. Such technologies can augment collective intelligence and facilitate knowledge creation. Conducting a case study of Shanghai, Zhou et al. (2023) examine the integration of social interaction and human activities into CDT research and development, highlighting the topic as an area for future research. Furthermore, Yue, Mao, and Zhao (2022) underscore the capability of digital twins to strengthen urban governance, especially concerning ecological environments. Bueti and Menon (2023) emphasizes that smart city research should prioritize the implementation of governance frameworks, rather than solely concentrating on technology adoption and deployment. However, critical discussions on this perspective remain scant (Pereira et al., 2023). For example, how CDTs can tackle governance challenges inherent in smart cities is understudied.

Maturity model

A maturity model serves as an effective tool for appraising the current status of digital technologies. Defined as a framework that evaluates a technology's level of maturity, quality, competency, sophistication, or progress toward a set goal (Becker et al., 2009; Warnecke et al., 2019), a maturity model has been used to assess the current status of development and risks and opportunities of various digital transformation technologies (Teichert, 2019). This includes applications within the areas of smart city (Aljowder, Ali, & Kurnia, 2019; Warnecke et al., 2019), IT industry (Wendler, 2012), e-governments (Cheikhi, Fath-Allah, Al-Qutaish, Idri, & Abran, 2023), transportation (Hausladen & Schosser, 2020), among others. In the area of smart cities, Aljowder et al. (2019) analyze diverse maturity models, noting that the frameworks employed differ significantly in their methodologies and domains. Shemyakina, Gorelova, and Dyudyun

(2022) suggest that a maturity model for CDTs should cover all life stages of the technological development. Such models offer insights into development status, potential risks, and opportunities while forecasting the CDT's technological advancement. However, the application of a maturity model specific to CDTs remains underdeveloped in the current literature. Thus, it becomes crucial to develop a maturity model for CDTs and investigate how it can offer a systematic framework to evaluate the development and potential of CDT initiatives (Masoumi, Shirowzhan, Eskandarpour, & Pettit, 2023).

3. Methods

We develop a maturity model that contains preliminary to advanced stages, designed after a literature review and survey of presently available models by finding their primary similarities. To conduct this research, we have surveyed several categories of the literature. First, we identified existing CDT projects from these selected articles and by searching publicly available sources. We selected initiatives with the following criteria: i) one that has their project information publicly available online, and, alternatively, one that was published in a publication. ii) city-scale projects, not district or building-scale projects. Second, we examined the current academic journal papers based on a set of search strings that included terms associated with city, urban, digital twins, governance, and maturity. Lastly, publicly available documents and reports from companies and governments were examined. Please note that we don't focus on the comprehensive, systematic review of the current literature about a CDT. Rather, we aim to propose a conceptual framework of a maturity model for a CDT and discuss the CDT's implication for urban governance.

4. A maturity model for CDT: CITYSTEPS Maturity Model

We have developed a maturity model framework by combining the Maturity Model of DUET and the project-wide maturity model by Arup (2019) and White, Zink, Codecá, and Clarke (2021), as depicted in Table 1. In constructing this model, we employed the characteristics of the input data and the desired outputs to categorize each phase of the maturity model.

Our framework has been developed such that each maturity stage corresponds to a specific stage of development along the desired path from the initial development stage (i.e., planning and preparation in our model) to the most advanced phase representing total maturity (i.e., real-time synchronization and autonomous implementation stage in our model). We define each maturity stage based on a comprehensive set of widely accepted and generalizable criteria, taking into account existing models in the public, private, and academic sectors, namely those developed by a public project (i.e., DUET), a private company (i.e., Arup (2019)), and an academic paper (i.e., White et al. (2021)).

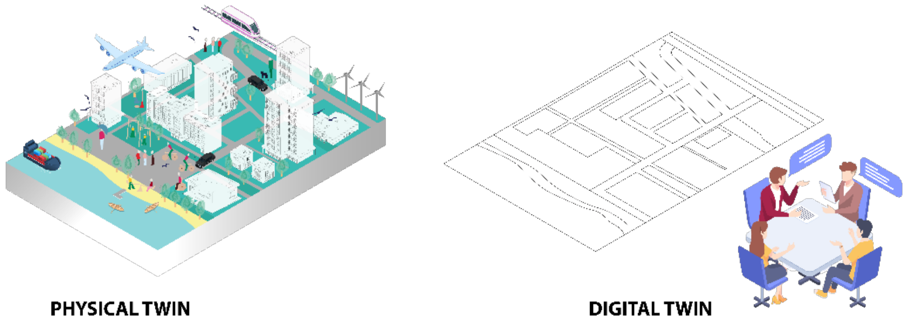
The model comprises the following eight stages (Figure 1):

- *Stage 1: Preparation and Planning Stage.* This initial stage involves planning and creating a framework for a digital twin. During this phase, no data is included. This stage includes deciding where a completed CDT will be open to the public or used only by policymakers (D'Hauwers et al., 2021).
- *Stage 2: 2D Stage.* The second stage focuses on the reconstruction of a physical city into a 2D model, incorporating essential land information and integrating various map types.
- *Stage 3: 3D Static Stage.* Using static data, the third stage builds a digital city within a 3D model. These data include building information details from Building Information Modeling (BIM) and infrastructure data for existing structures. At this stage, the digital twin evaluates both historical and present situations, predicting impacts using 3D static data. For example, it assesses the built environment, such as shades and landscapes. The 3D BAG project in the Netherlands can be

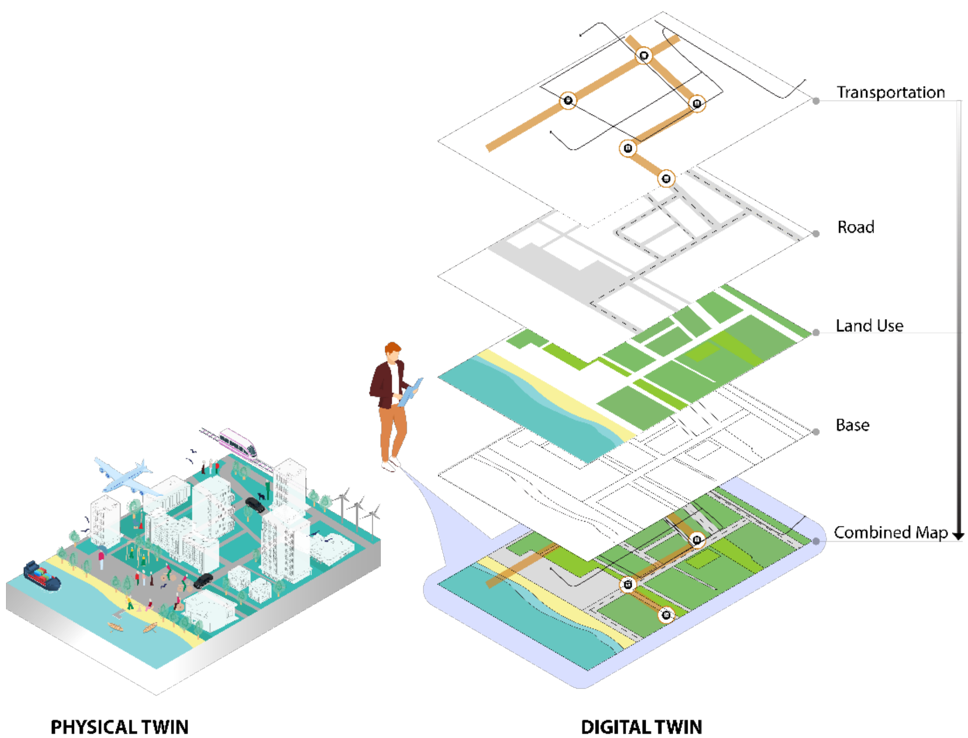
classified as Stage 3 as it aims to create a 3D model that includes geography, elevation, and building features (3D Geoinformation Research Group, 2022).

- *Stage 4: 3D Dynamic Stage.* This stage equips the model with 3D structured and dynamic data, including human mobility, transportation, and the flow of goods. The model integrates large amounts of urban data to facilitate predictions and simulations. For example, a model can simulate building electricity usage, traffic congestion, or urban air circulation patterns. A prime example is the OnDijon project in Dijon, France, which aligns with Stage 4 in our framework. The project uses integrated dynamic data to conduct impact simulations, incorporating data from all public utilities and services to analyze the present environment (Dijon Metropole).
- *Stage 5: Dynamically Integrated 3D Stage*. In this phase, a CDT model evolves to incorporate 3D dynamic and IoT data. This indicates a shift from earlier stages, where the digital city replicated its physical counterpart. From Stage 5 onwards, the model can include virtual structures or buildings that do not have physical counterparts. Furthermore, it begins to provide recommendations to aid human decision-making processes. A notable example of this is a project in the City of Zurich in Switzerland, which involves simulation analysis based on already collected data (Schrotter & Hürzeler, 2020). It simulates urban environmental phenomena, including noise, air pollution, and solar potentials, by integrating and analyzing geometric data with various planning parameters, such as building utilization, floor space, and number of inhabitants and workplaces. The City Information Model (CIM) contributes to this stage, extending the BIM concept to cover the entire city, transforming static CDTs into dynamic ones (Cureton & Dunn, 2021; Wu et al., 2021).
- *Stage 6: Real-time Decision-making Stage.* At this stage, CDTs gain the capabilities to analyze dynamic and integrated 3D data, offering accurate insights and real-time alternative options for decision-making. They can also simulate impacts across different domains. Among European projects, the National Digital Twin program (NDTp) exemplifies this stage for its prioritization of the real-time data processing, focusing on real-time analysis and reactive event processing (Cambridge Living Laboratory Research Facility, 2022). Similarly, DUET utilizes ten data sources and 18 simulation models to inform planning decisions (DUET, 2022a). Both projects can be classified as Stage 6 in our framework, presenting the capabilities to derive optimal solutions through real-time analysis using dynamic and integrated data.
- *Stage 7: Autonomous Decision-making Stage*. At this stage, the digital twin uses autonomous reasoning and artificial intelligence to make decisions independently and execute actions based on 3D predictions and simulations. Currently, there are no known existing projects that have reached this stage.
- *Stage 8: Real-time synchronization and autonomous implementation stage*. This stage sees CDTs achieve full, bidirectional, continuous, real-time synchronization between the physical reality and the digital counterpart. During this phase, CDTs autonomously implement decisions, guided by insights from simulations.

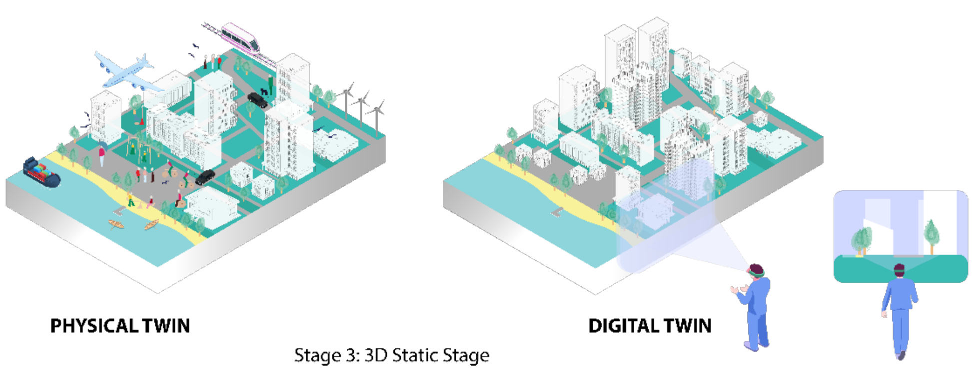
We introduce our innovative maturity model for CDTs as *CITYSTEPS*, encapsulating all eight stages of our framework: **C**onception & Planning (Stage 1), **I**nitiation with 2D (Stage 2), **T**ransition to 3D Static (Stage 3), **Y**ielding Dynamic 3D Models (Stage 4), **S**tructured Dynamic Integration (Stage 5), **T**actical Real-time Decisions (Stage 6), **E**mbedded Autonomous Decisions (Stage 7), and **P**roactive Real-time Synchronization and **S**elf-actualized Implementation (Stage 8).



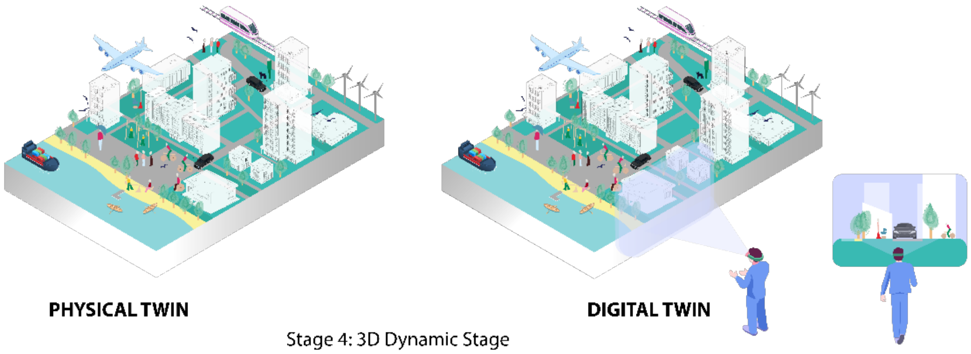
Stage 1: Preparation and Planning Stage



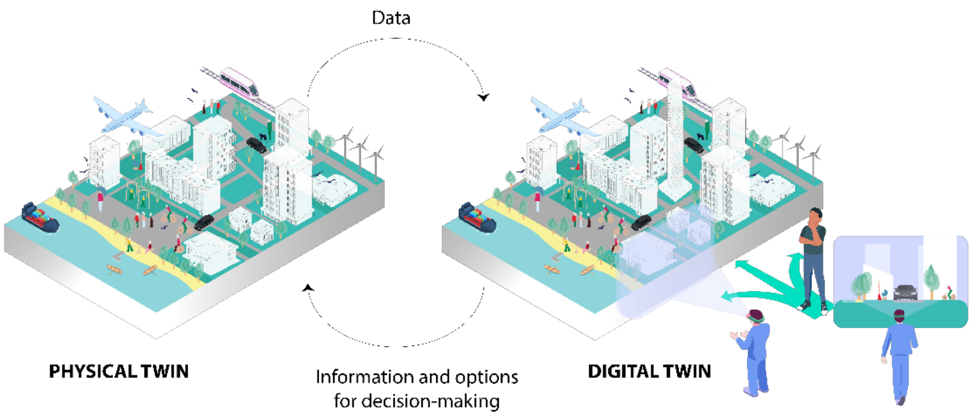
Stage 2: 2D Stage



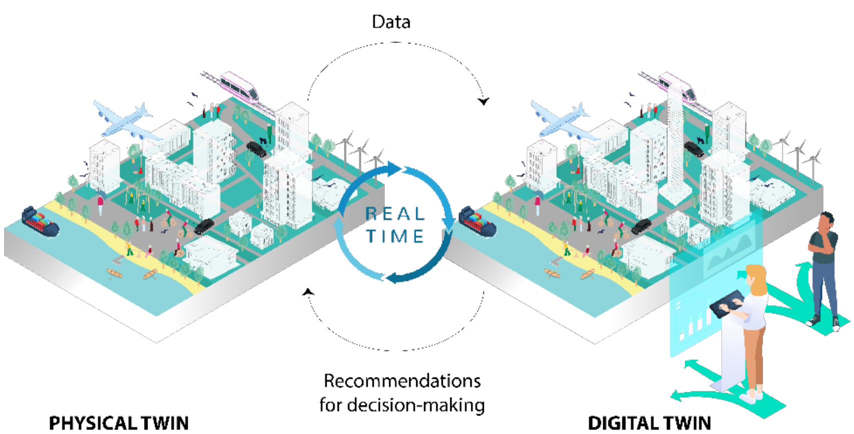
Stage 3: 3D Static Stage



Stage 4: 3D Dynamic Stage



Stage 5: Dynamically Integrated 3D Stage



Stage 6: Real-time Decision-Making Stage

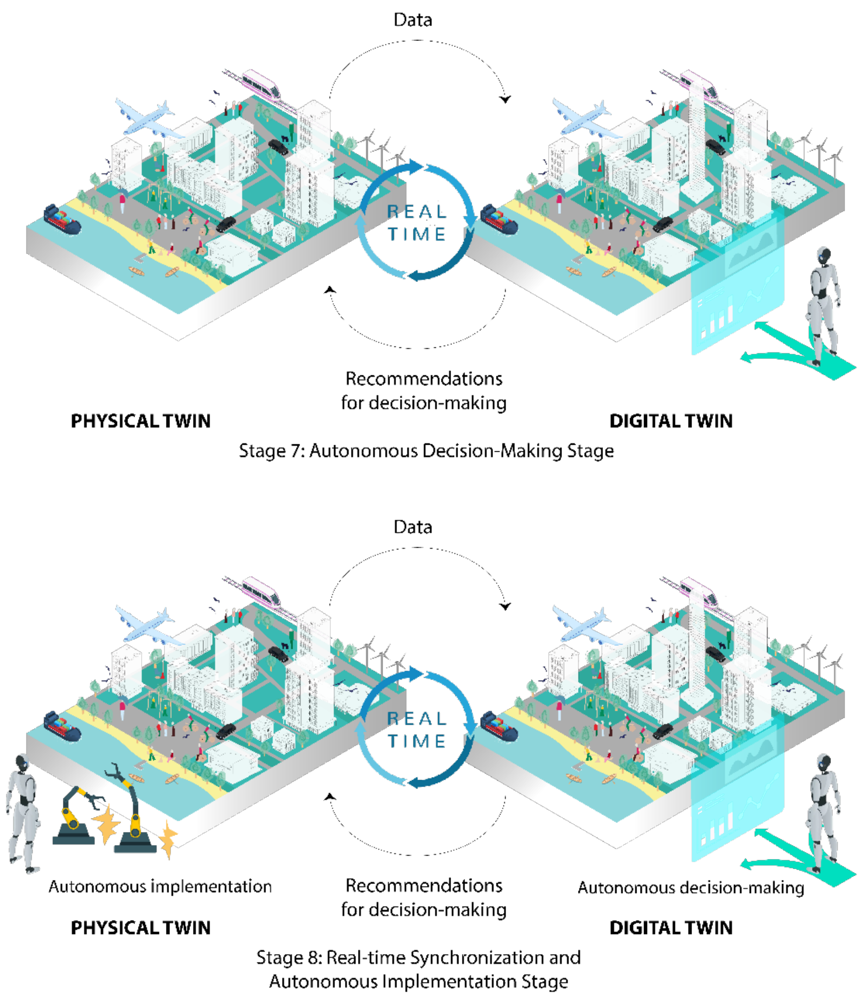


Figure 1: Our proposed maturity model, CITYSTEPS Maturity model. They have eight stages. Stage 1: Preparation and planning stage; Stage 2: 2D stage; Stage 3: 3D static stage; Stage 4: 3D dynamic stage; Stage 5: Dynamically Integrated 3D Stage; Stage 6: Real-time decision-making stage; Stage 7: Autonomous decision-making stage; and Stage 8: Real-time synchronization and autonomous implementation stage.

Table 1:Our novel framework of maturity model, CITYSTEPS Maturity Model, and existing frameworks of maturity model of CDT.

Our novel framework (CITYSTEPS Maturity Model)			**Existing frameworks**		
Stage	Input data	Examples of what we can do using CDT for disaster evacuation	Gary White et al.(2021)	DUET(2022)	ARUP(2019)
1: Preparation and Planning Stage. Planning & making a framework	No data			**Awareness of Twins** The political desire to create/ adopt Digital Twin for better evidence-based decision-making. Aligns with the administration's existing digital transformation and smart city strategies.	
2: 2D Stage. Reconstructing a physical city into a 2D model.	2D data	• Indicate evacuation routes. • Identify high-risk areas in 2D.	**0- Terrain** Basic land information about the city (2D)		
3: 3D Static Stage. Building a digital city within a 3D model to simulate the past and present situations and make impact predictions using static 3D data.	3D static data	• Indicate evacuation routes. • Identify high-risk areas in 3D.	**1-Buildings** Building information, including BIM models (3D) **2-Infrastructure** Information about Infrastructure which surrounds the current buildings in the city (3D)	**Experimental Twins** Brings together a small number of structured urban datasets for a specific use case involving two domains. Impact predicted on limited static data sets and sources. Able to make decisions based on historical data.	**Level 1** A digital model linked to the real-world system but lacking intelligence, learning, or autonomy; limited functionality **Level 2** A digital model with some capacity for feedback and control, often limited to the modeling of small-scale systems
4: 3D Dynamic Stage. Understanding the current situations and conducting simulations of dynamic data including human mobility and activities.	• 3D structured data. • 3D spatiotemporally dynamic data.	• Simulate human flow and damages during and after disasters.	**3-Mobility** Information about the movement of people during their daily routine and the movement of the goods that help them in different aspects of their lives **4-Digital Layer /Smart City** gathering all the data needed for simulations in the virtual layer/digital twin from all the previous layers	**Predictive Twins** Integrates large numbers of structured urban data sets for multiple use cases across more than two domains. Impact predicted using advanced data models and simulations. Able to inform near real-time decisions.	**Level 3** A digital model able to provide predictive maintenance, analytics, and insights **Level 4** A digital model with the capacity to learn efficiently from various sources of data, including the surrounding environment. The model will have the ability to use that learning for autonomous decision-making within a given domain
5: Dynamically integrated 3D stage. Integrating dynamic and IoT data to offer options for decision-making.	• 3D dynamic data • IoT data	• Provide options for evacuation routes based on disaster damage estimation and human flow simulation during evacuation.	**5-Virtual Layer /Digital Twin** Conduct simulations in the virtual layer, which can then be passed back as information through the layers of the city		
6: Real-time Decision-making Stage. Analyzing dynamic and integrated 3D data to offer accurate insights and real-time alternative options for human decision-making.	• 3D dynamic data • IoT data • Structured and unstructured data	• Propose the most effective evacuation routes based on disaster damage estimation and human flow simulation during evacuation.		**Intelligent Twin** It uses **structured and unstructured data** for cross-domain impact modeling. Twin uses AI to learn and make real-time accurate insights and predictions. Able to accurately align real-time operational decisions with longer-term policy.	

7: Autonomous Decision-making Stage. Making decision-making and executing actions independently, derived from autonomous reasoning.	Predicted and simulated data	• Select the most effective evacuation route based on disaster damage estimation and human flow simulation during an evacuation, and automatically seal off risky routes.			**Level 5** A digital model with a wider range of capacities and responsibilities, ultimately approaching the ability to autonomously reason and to act on behalf of users (artificial general intelligence).
8: Real-time Synchronization and Autonomous Implementation Stage Achieving full, bidirectional, continuous real-time synchronization between reality and the digital twin and autonomously implementing decisions.		• Autonomously adjust the evacuation route in response to changes in the environment. After the first autonomous creation of an evacuation route, the digital twin will be able to identify and respond to new hazards or obstacles that arise during an actual evacuation.			

Note: an upper-level stage includes all input data and functions from the below stages.

5. Analysis of Governance of CDTs

5.1. Transparency

Transparency refers to the availability and accessibility of information to the citizen. It means that information is readily available and easy to understand, and that decision-making processes are open and understandable (Jacobs et al., 2020). Along with concreteness, transparency was one of the main advantages of CDTs among users who responded to a questionnaire by Dembski, Wössner, Letzgus, Ruddat, and Yamu (2020).

The concept of transparency varies across different stages of our CITYSTEPS Maturity Model. In Stage 1, the planning and preparation stage, we evaluate existing plan documents, including guidelines and specifications. This evaluation aims to assess how well these documents ensure transparency for future implementation and improvement. For example, NDTp, which focuses on the development of CDTs, publishes a number of plans related to the framework in its development. Four of the nine published plans and reports directly pertain to the framework. This includes the Gemini Principle – proposed guidelines to direct the national digital twin in the United Kingdom and the information management framework (The Centre for Digital Built Britain; Wan et al., 2019).

In the phases after planning and preparation, the concept of transparency takes on varied interpretations, particularly in the context of CDTs for urban governance. Initially, we pay attention to data accessibility. Some projects make their data accessibility policies clear. For example, since 2012, the City of Zurich has made data from its public administration freely available, in a machine-readable format and under a free license. Similarly, 3D BAG in the Netherlands is licensed under CC BY 4.0 (Please refer to the Supplementary Document for case studies of CDTs in the EU).

Moreover, the transparency of decision-making processes becomes paramount beyond Stage 7, which introduces autonomous decision-making components into the Digital Twin. Like the discourse around trustworthy artificial intelligence (AI) (Taeihagh, 2021), there are rising concerns that CDTs may not provide the level of transparency needed for thorough inspection and understanding of automated decision-making processes. This lack of transparency can undermine political legitimacy within governments (Eom, 2022; B. T. Wang & Burdon, 2021).

5.2. Accountability

Accountability is defined as the obligation of decision-makers and implementers to justify their actions and outcomes (Jacobs et al., 2020). There are several ways of assessing project accountability in the context of the governance of CDTs. For example, evaluating the project's accountability involves reviewing whether the CDT technology's design and implementation adhere to open data licensing frameworks and privacy regulations. First, reports documenting past project implementations can serve as accountability tools. The DUET project, for instance, has published reports on each area of CDT implementation (i.e., data management, privacy, and CDT construction and analysis techniques), alongside regular updates on pilot projects and strategic plans for data operations and decision-making processes (DUET, 2022b). These include evaluations of completed pilot projects, which are made publicly accessible. Moreover, a range of related documents, such as Ethical Principles for Utilizing Data-Driven Decision-making in the Cloud (It.2), as well as Policy Briefs, have been published. Also, the Zurich project has published terms of use, product descriptions, and reports on technology for public CDTs (Stadt Zürich).

Furthermore, documents regarding privacy guidelines and standards enhance project accountability. For example, DUET has released several legal and privacy-related plans and guidelines, including the Legal Landscape and Requirements Plan and Privacy Impact Assessments (PIAs). Projects in the EU that we analyze explicitly state that their guideline follows the General Data Protection Regulation (GDPR) (e.g., DUET and OnDijon) while establishing an ethics and data governance committee (e.g., OnDijon in Dijon France). Therefore, accountability within CDT projects can be assessed at each project development phase.

Upon implementing a CDT project, the concept of accountability revolves around the decision-making process. As decisions rooted in CDTs emerge post Stage 5, it necessitates the inquiry into who holds responsibility for those decisions (Ketzler et al., 2020). This question grows in significance, especially during Stages 7 and 8 when CDTs and AI take on roles of autonomous decision-making.

5.3. Inclusion

Inclusion refers to the equitable presence of all citizens, including marginalized and disadvantaged groups, in the benefits and opportunities provided by CDT initiatives (van Gils & Bailey, 2021). It means that every citizen has an equal opportunity to access and participate in the services and infrastructure provided by CDT. Through our investigation of existing projects, inclusion is barely discussed in the context of CDT, as claimed by Tzachor (2022). We will discuss this issue later in Section 7.

5.4. Participation

Public participation refers to the active engagement of citizens and stakeholders in the decision-making and implementation process, intending to be inclusive. Public participation is regarded as "a cornerstone of democracy" (Roberts, 2004), meaning that the legitimacy of democracy relies on the quality of public decision-making through participation (Kleinhans, Falco, & Babelon, 2022). Public participation is also vital to sustainability (Kleinhans et al., 2022). Furthermore, current urban planning processes are characterized by a specific form of participation, co-production, which is between experts and the public (Kleinhans et al., 2022). The Internet enables coproduction at an unprecedented scale by removing constraints in time and space (Linders, 2012). CDTs can be a particular type of technology that can enhance public participation in general and co-production specifically (Ludlow, 2023; Lv, Shang, & Guizani, 2022). Namely, public participation involves giving citizens the opportunity to provide input and feedback on CDT projects and considering their opinions when making and implementing decisions. If it is co-production, the public sector and citizens strive to achieve better outcomes by utilizing each other's assets and resources (Bovaird & Loeffler, 2012).

There is a clear distinction between public participation and inclusion. Participation is critical for creating and implementing CDT initiatives that are responsive to the demands and concerns of citizens. Inclusiveness, on the other hand, means being inclusive of a wide range of urban residents regardless of their economic status, gender, race, ethnicity, or religion. While participation means increasing public input on city planning and issues, it can be achieved by a certain group of urban citizens. However, participation that is inclusive of all citizens would be more desirable.

CDTs offer a promising pathway to amplify citizen participation in urban planning, which in turn can bolster urban governance. First, by enhancing planning processes, CDTs facilitate decision-making in a more intuitive way. For instance, the visual elements within CDTs allow citizens to grasp simulation results more intuitively (Dembski et al., 2020). Second, the interactive and user-friendly interfaces of CDTs foster enriched interactions among decision-makers, urban planners, and the general populace. A practical application of this is evident when citizens, using just their smartphones, can highlight urban issues, such as a broken streetlight, simply by sharing a photo (Ham & Kim, 2020; White et al., 2021). Further, the third advantage lies in CDTs' capability to simulate policy options. While implementing and testing policies in real-world settings poses challenges, CDTs offer a virtual space to do so. Citizens have engaged in virtual games or simulations on CDT platforms, granting urban planners invaluable feedback on proposed plans. This approach has been utilized in cities, such as Zurich (Schrotter & Hürzeler, 2020) and Herrenberg, Germany (Dembski et al., 2020). Lastly, CDTs can serve as open platforms, mirroring the functionalities of OpenStreetMap and Maptionnaire. An illustrative example is Japan's Project PLATEAU, which empowers users to craft their own apps, games, and simulations (Seto, Furuhashi, & Uchiyama, 2023).

Upon examining existing CDT projects, we identify two types of citizen participation: one is in designing CDT projects, and the other is in implementing and using CDTs for decision-making for urban planning. EU's DUET project allows citizens to participate in their CDT project's design and development processes. An interview with each stakeholder, including citizens, was conducted to identify the functions that should be included in the CDT, using an agile methodology (DUET, 20 July 2020). The stakeholders participated in the project from the early development planning stage. Their perspectives and opinions about the CDT were summarized and considered in evaluating development priorities. Notably, 12 of the 18 summarized public opinions were from citizens (DUET, 20 July 2020).

On the other hand, other projects aim to use CDTs to promote citizen participation for the improvement of urban governance. For example, under Zurich's and OnDijon's initiatives, citizens are encouraged to participate in the use and implementation of CDT technologies. Under OnDijon, they have developed a system in which information entered through a smartphone app is linked to a digital model, and citizens have played the role of information providers (Dijon Metropole). Zurich's project also developed a game using the created digital model. By encouraging citizens to use the game widely, they worked to gather interest and opinions from citizens and obtained feedback from them (Schrotter & Hürzeler, 2020). Furthermore, in the 3D BAG, citizens provided feedback on a model used in the application phase. At the same time, interviews and workshops were conducted during the planning phase in NDTp in the UK to collect public opinions (Nochta et al., 2021).

CDT can serve as more evidence-based decision-making and participatory and co-production tools for citizens by overcoming the time and space challenges of traditional participatory methods (Perikangas & Tuurnas, 2023). Good networking through CDT can increase participation opportunities for citizens and their access to the administration (Ketzler et al., 2020; Schrotter & Hürzeler, 2020). In Zurich, a web-based, interactive 3D tool and computer game have been tested to increase digital participation within the city (Schrotter & Hürzeler, 2020). One of the benefits of the tested technologies is that participation is convenient as it enables participation from home at a flexible time (Schrotter & Hürzeler, 2020). Also, each level of the Maturity Model has different roles of citizen participation, from data provision to decision-making (Table 2).

Kleinhans et al. (2022) argue that one of the four critical conditions for active public participation or co-production is "phygital', which blends both digital and in-person (i.e., physical) methods. Some projects, such as the EU's DUET and the National Digital Twin program (NDTp) of the UK, meet this criterion by ensuring that citizens are engaged through both in-person meetings and online experiments throughout the project process. Moreover, the evacuation example outlined in Table 2 illustrates a "phygital" approach. Initially, citizens would simulate evacuation in a digital twin space to experience the scenario virtually. Subsequently, they would participate in a physical evacuation exercise. In both cases, participants are requested to provide feedback.

Table 2: The role of citizen participation in each CITYSTEPS Maturity model's stage with disaster evacuation examples.

Maturity model level	The role of citizen participation	Examples of the role of citizen participation in disaster evacuation
Stage 1: Preparation and Planning Stage. Planning & making a framework	- Provide input on CDT plans	- Participate in and provide input for planning decisions regarding disaster risk management and evacuation procedures.
Stage 2: 2D Stage. Reconstructing a physical city into a 2D model.	- Share data, information, and insights relevant to the CDT. - Provide opinions and feedback on 2D CDT products.	- Provide 2D information on high-risk areas, such as damaged roads and flood levels. - Provide feedback on evacuation routes.
Stage 3: 3D Static Stage. Building a digital city within a 3D model to simulate the past and present situations and make impact predictions using static 3D data.	- Share static data, information, and insights relevant to the CDT. - Provide opinions and feedback on 3D CDT products.	- Provide 3D information on high-risk areas, such as broken windows and roofs, the height of debris, etc. - Provide feedback on evacuation routes, including vertical evacuation to tall buildings or underground areas.
Stage 4: 3D Dynamic Stage. Understanding the current situations and conducting simulations of dynamic data including human mobility and activities.	- Provide data, information, and insights on human mobility patterns and transportation flows. - Provide opinions and feedback on 3D CDT products.	- Provide data and information on evacuation routes with GPS's spatiotemporal information. - Provide feedback on effective evacuation routes based on the disaster scale and evacuee retention trends discovered by CDT's simulations.
Stage 5: Dynamically Integrated 3D Stage. Integrating dynamic and IoT data to offer options for decision-making.	- Offer opinions and feedback on proposed recommendations for decision-making based on CDT simulation results. - Make decisions based on the CDT's recommendations, with some time lags.	- Select the most appropriate evacuation route option from those shown by CDT's simulations.
Stage 6: Real-Time Decision-Making Stage. Analyzing dynamic and integrated 3D data to offer accurate insights and real-time alternative options for human decision-making.	- Provide real-time data, information, and insights, including human mobility patterns. - Make real-time decisions based on the CDT's recommendations.	- Select the most appropriate evacuation route option from CDT's real-time simulations.
Stage 7: Autonomous Decision-Making Stage. Making decision-making and executing actions independently, derived from autonomous reasoning.	- Share feedback on the autonomous decision-making capabilities of CDTs.	- Provide feedback on automatically sealed-off risky routes and prompted evacuation actions based on CDT's real-time simulations.
Stage 8: Real-Time Synchronization and Autonomous Implementation Stage. Achieving full, bidirectional, continuous real-time synchronization between reality and the digital twin and autonomously implementing decisions.	- Share feedback on the autonomous decision-making and implementation capabilities of CDTs.	- Provide feedback on automatically sealed-off risky routes and prompted evacuation actions based on CDT's real-time simulations and citizen participation and feedback.

6. CDT's potentials for smart city development

Using CDT technology within the context of smart city development is a complex and multifaceted challenge. While CDT has the potential to provide significant support in certain areas, its capabilities also have limitations. CDT can be utilized as a tool to plan, manage, and accelerate smart city development (H. Wang, Chen, Jia, & Cheng, 2023; Yu, Lang, Galang, & Xu, 2023). By analyzing, simulating, and predicting diverse scenarios, decision-makers and stakeholders can make more informed decisions regarding smart city development with the support of CDT. In this section, we examine both the benefits and limitations of CDT regarding smart city development, exploring specific areas where CDT can effectively support smart city initiatives and areas where its impact is limited.

Previous studies by Silva, Khan, and Han (2018) and Rana et al. (2019) have identified the challenges of smart city implementation, such as the cost of design and operation, technological issues such as data collection and analysis, information security, and sustainability. In addition, the need for stakeholder participation, especially citizen participation, has been emphasized as a crucial factor for sustainable urban development (Bouzguenda, Alalouch, & Fava, 2019; Ju, Liu, & Feng, 2019; Razmjoo, Østergaard, Denai, Nezhad, & Mirjalili, 2021). These challenges have also been noted in the development of CDT (Lei, Janssen, et al., 2023). Thus, this section discusses how CDT can contribute to solving these challenges, building on the findings about smart city development and CDT of Rana et al. (2019) and Lei, Janssen, et al. (2023). We consolidate these barriers and challenges identified by the referenced papers and list them in Table 3.

The nature of CDTs, which can concretely demonstrate their effects through visualization (Lei, Stouffs, & Biljecki, 2023), allows for plans to be presented in a way that is easier for citizens to understand and engage with. This could help promote citizen participation and understanding (the key barriers 4 and 5 in Table 3) as identified by Rana et al. (2019) as smart cities' challenges. In particular, citizen participation is crucial at every stage of the CITYSTEPS Maturity Model. In Stage 1, citizens provide input on the plan, while in Stages 2 and 3, they contribute data. In Stage 4, citizens provide feedback and opinions on visualized policy outcomes, while in Stage 5, they offer feedback on the plan based on the visualized simulation of policy implementation. In Stage 6, citizens provide feedback on the optimal solution presented based on the simulation. Furthermore, citizen's understanding and awareness of the technology increase during Stages 2 and 3 of the Maturity Model. In these stages, citizens provide information for the CDT model, allowing for their active participation and resulting in a bottom-up approach that improves the model's accuracy. This data collection by the citizens themselves can enhance their engagement, increase the sense of community, and empower them to contribute to the CDT initiative.

CDT enables the integration of diverse urban information into virtual reality, facilitating the visualization and connection of smart city technologies through standardized CDT technologies (the key barrier 3 identified by Rana et al. (2019) and listed in Table 3). In the fifth stage of our Maturity Model, data collected using IoT technology can be aggregated into one model and visualized as digital twins. In this stage, the CDT model serves as a common information system model, promoting the efficient sharing and utilization of information.

Nevertheless, challenges remain in reestablishing trust between the public and private sectors (the key barrier 1). To address this, visual representation can enhance accountability and transparency. The visualization capabilities of CDTs, as illustrated in the fourth stage of the Maturity Model, can intuitively demonstrate potential policy outcomes. Furthermore, in the fifth stage, the decision-making process can be presented more transparently through the visualization of policy impacts, making them more accessible to citizens. Consequently, CDT is instrumental in establishing greater trust, particularly regarding accountability and transparency.

Collaboration with numerous private and public stakeholders, including citizens, presents challenges related to leadership in data management and operation (the key barrier 2). Promoting public-private collaboration through CDT initiatives is necessary to address these challenges. The fourth phase of our Maturity Model integrates multiple data sets and simulates impacts, enabling specific impact assessments with visualization images, which could incentivize greater private sector participation. However, to make this possible, rules and regulations must be established.

Standardization is challenging in implementing CDT (Lei, Janssen, et al., 2023). However, advanced digital twin technology can integrate and consume specific data sets in various formats and standards (Boje, Guerriero, Kubicki, & Rezgui, 2020). Standardization can be partially achieved in the fifth step of our Maturity Model, where information from diverse fields is integrated into a single model. This is because data generated under different criteria can be aggregated and utilized within a single model in this stage.

CDTs also face similar challenges as other smart cities regarding data disclosure regulations and accessibility (the key barrier 7), transparency and accountability (the key barrier 8), and privacy protection (the key barrier 9). Current approaches to CDTs have not yet resulted in solutions to these pressing issues, which will be discussed in Section 7.

In summary, the CDT approach to smart city challenges has the potential to effectively promote citizen participation through digital visualization. However, in public-private collaboration, challenges remain, such as organizing stakeholder relationships and developing laws and regulations. Depending on each development stage of the maturity model, it is crucial to coordinate stakeholder involvement and make institutional arrangements to maximize the synergy between CDTs and smart city development.

Table 3: Key barriers to smart city development and how CDT can address smart city's challenges.

Key Barriers[1]	**Description**[1]	**Causes of smart city barriers**	**Whether CDT is a solution to the Smart City's challenges?**[2] **How CDT can address Smart City's challenges**	**Stage in the CITYSTEPS Maturity Model for Overcoming Barriers: Explanations**
1: Lack of trust between the governed and government	Lack of trust between the government and people can impede smart city development (Balta-Ozkan, Davidson, Bicket, & Whitmarsh, 2013; Monzon, 2015).	Privacy and security issue	△: CDT facilitates communication between citizens and government through visualization (Dembski et al., 2020), but it is unclear whether it can be a means of restoring trust.	**Stages 4 and 5** - The visualization can be used to explain policy results in the fourth stage of our Maturity Model. - In the fifth stage, decision-making can be made more transparent to citizens by visualizing the projected impact of policy implementation.
2: Poor private-public participation	Poor private-public interaction can negatively impact smart city development projects (Koppenjan & Enserink, 2009; J. H. Lee, Hancock, & Hu, 2014).	Lack of regulation and incentives	△: Collaboration with private stakeholders is also a challenge for CDT(Nochta, Badstuber, & Wahby, 2019). On the other hand, strategy development using CDT modeling promotes discussion/collaboration between the public and private sectors, including citizens(Nishino, Kodaka, Nakajima, & Kohtake, 2021).	**Stages 4 and 5** The fourth phase of our Maturity Model enables impact assessments with visualization images, which could incentivize greater private-sector participation.
3: Lack of developing a common information system model	Lack of a common information system model to ensure end-to-end visibility while managing smart city infrastructure and services (Ballon et al., 2011; Naphade, Banavar, Harrison, Paraszczak, & Morris, 2011).	Lack of infrastructure and methodology to effectively share and use information	✓ : The CDT model enables connectivity and visualization of Smart city technologies (Deng, Zhang, & Shen, 2021).	**Stage 5** - CDT model enables connectivity and visualization of Smart city technologies (Deng et al., 2021). - Specifically, in the fifth stage of our Maturity Model, data collected using IoT technology can be aggregated into one model and visualized as digital twins.
4: Lack of involvement of citizens	The absence of citizen participation is evident in how smart cities are envisioned and experienced. The citizens should be encouraged to submit and evaluate ideas for innovation in smart city	Lack of a system to accommodate citizen participation Lack of digital skills of citizens	✓ : CDTs can be a means of encouraging citizen participation (Dembski et al., 2020).	**Stage 1, 2, 3, 4, and 5.** Citizen involvement is crucial at every stage of the maturity model. Stage 1: citizens provide input on the plan. Stages 2 and 3: they contribute data. Stage 4: citizens provide feedback on visualized policy outcomes.

	design (IET, 2017; Kogan & Lee, 2014; Komninos et al., 2013; Schuurman et al., 2012).			Stage 5: they offer feedback on the plan based on the visualized simulation of policy implementation. Stage 6: citizens provide feedback on the optimal solution.
5: Low awareness level of community	The public lacks an understanding of the idea of a smart city and its implications on their quality of life (IET, 2017; Kogan & Lee, 2014).	Top-down approach	✓ : CDT can present the impact on the lives of citizens intuitively so that many people can easily understand through simulation and visualization (Deckert, Dembski, Ulmer, Ruddat, & Wössner, 2020; Deng et al., 2021).	**Stage 2 and 3.** By providing information for the CDT model, citizens actively contribute to the initiative through a bottom-up approach, increasing the understanding of the city's digital technology.
6: Lacking standardization	Lack of standardization across indicators (e.g., smart technologies, security, privacy, quality of life, environmental sustainability, physical infrastructure, mobile networks, etc.) has emerged as one of the crucial hindrances in the smart city context (Bhattacharya, Rathi, Patro, & Tepa, 2015; Kogan & Lee, 2014).	The heterogeneity and different ownership of data make the process of establishing comprehensive standards and regulations very complex.	△: In the CDT, standardization within the integrated model is also challenging (Lei et al., 2023). On the other hand, Boje et al. (2020) describe Digital Twin as able to integrate and consume specific data sets in its various formats and standards.	**Stage 5** In Stage 5, where information from diverse fields is integrated into a single model, standardization can be partially achieved because data generated under different criteria can be aggregated and utilized within a single model.
7: Issues of openness of data	Open data and its accessibility are issues in smart cities, and they can impede how smart city services can be delivered to cities' residents and businesses (Kogan & Lee, 2014).	Privacy and security issues	✗: The regulation of data publication and its accessibility is also challenging in the CDT (Lei, Janssen, et al., 2023).	Openness and privacy remain essential issues at all stages of our Maturity model.
8: Lack of transparency and liability	Inhibited transparency and unclear lines of political accountability in delivering most services could be a concern for smart city	Lack of coordination of interests among stakeholders (concepts, visions, goals, plans, etc.)	✗: Transparency and accountability (political accountability) are also challenging in the CDT(Lei, Janssen, et al., 2023).	Transparency and liability remain essential issues at all stages.

	development. The lack of transparency risks isolating the very people smart city technology should serve (Nam & Pardo, 2011).			
9: Lack of regulatory norms, policies, and directions	There is a lack of appropriate laws, regulations, or directives for the development of smart cities (Chourabi et al., 2012).	Legal development requires considering a multitude of regulations at various levels of implementation, such as local, governmental, and national levels.	✗ : In the CDT, legal development is insufficient (El Saddik, 2018).	Regulatory norms, policies, and directions remain essential issues at all stages.
Note 1: Key barriers to smart city development and their description are referred from Rana et al. (2019). **Note 2: ✓ indicates that CDT can be a solution to the respective smart city issue, while ✗ indicates that CDT cannot be a solution. Finally, △ indicates that CDT can be a part of the solution to the smart city issue.**				

7. CDT's challenges in technology development and governance

Several technical and non-technical challenges can interrupt the CDT development.

7.1. Interoperability

Interoperability is a significant challenge in CDT (Lei, Janssen, et al., 2023; Quek et al., 2023). The main barrier is converting data between systems, which requires common conversion paths but is a complex task due to differences in encoding, semantic coherence, geometric validation, coordinate reference system, and topological accuracy (Floros, Pispidikis, & Dimopoulou, 2017; Lei, Janssen, et al., 2023). Software compatibility is also challenging (Lei, Janssen, et al., 2023; Quek et al., 2023). For example, importing 3D GIS data into BIM models is challenging due to a lack of support from BIM-related software (Biljecki, Stouffs, & Kalantari, 2021; Lei, Janssen, et al., 2023). Commercial software (e.g., CityEngine) has been developed to support integration, but standards are not aligned, and some software doesn't support semantic compatibility with the CityGML standard (Lei, Janssen, et al., 2023; Muñumer Herrero, Ellul, & Morley, 2018).

Both industry and academia have proposed various solutions (Lehtola et al., 2022). Among different approaches, Quek et al. (2023) discusses the concept of a knowledge graph. This tool is designed to describe and depict objects and their interrelations, functioning as a knowledge management system to facilitate data addition and retrieval. Distinctly, this proposal leverages semantic integration, diverging from conventional system integrations (Quek et al., 2023). On the industry front, Microsoft Azure, a cloud computing platform, developed and open-sourced the Digital Twin Definition Language (DTDL) — a modeling language tailored to articulate models and interfaces for digital twins (Russom). In partnership with RealEstateCore, they launched the DTDL-anchored RealEstateCore ontology. This provides a standardized platform to architect smart buildings in line with established industry standards and guarantees compatibility among various DTDL-based solutions from multiple providers (Russom).

7.2. Data integration

Data integration is a significant hurdle, with heterogeneous data collection and incompatible systems being key concerns (Biljecki, Lim, et al., 2021; Gil, 2020; Lei, Janssen, et al., 2023). Heterogeneous data, such as crowdsourced and 3D geospatial data, poses issues in integration (Biljecki, Lim, et al., 2021; Deng et al., 2021). Incompatible systems, such as different coordinate systems between BIM and GIS data, also impact efficiency and resource usage (Biljecki, Lim, et al., 2021; Gil, 2020; Xia, Liu, Efremochkina, Liu, & Lin, 2022).

Various initiatives and research attempt to address data integration challenges. Jeddoub, Nys, Hajji, and Billen (2023) argue for a tri-level approach to data integration: first, at a conceptual schema model-based level; second, at a database level; and lastly, at an application-centric level. The integration approach must be contingent upon available data types, sources, and acquisition methods. It is critical to consider not just the geometric dimensions but also the intricacies of semantics, structure, and storage methodologies (Jeddoub et al., 2023). For an integration of BIM and GIS, they advocate for the Application Domain Extensions (ADEs) to extend the CityGML standard, a mechanism that has been a popular means of advancing data integration (Uggla et al., 2023). In parallel, the FIWARE smart data model stands as a testament to harmonizing data across over 200 cities globally (Bauer, Cirillo, Fürst, Solmaz, & Kovacs, 2021). The model is rooted in NGSI-LD (Next Generation Service Interfaces-Linked Data) – a standard ratified by ETSI (European Telecommunications Standardization Institute) – and ensures consistent data formatting across diverse platforms. The NGSI-LD standard is supported by the European Connecting Europe Facility, the Open and Agile Smart City community, the Indian Urban Data Exchange platform, and the Japanese Smart City Reference Model (Bauer et al., 2021; Cirillo et al., 2019). Furthermore, the availability of common exchange vector formats, such as IFC and IndoorGML, in tandem with streaming formats like OGC 3D Tiles and GeoJson-LD, paves the way for real-time, efficient data transfers even for voluminous datasets (Li, Conti, Konstantinidis, Zlatanova, & Bamidis, 2019; Weil, Bibri, Longchamp, Golay, & Alahi, 2023). A comprehensive list of these formats can be gleaned from Weil et al. (2023).

7.3. Privacy protection

Privacy has been a significant issue in CDT, as has human mobility data (Ketzler et al., 2020). Anonymized data and techniques are available; however, considerable challenges remain (Ramu et al., 2022; Saranya & Amutha, 2023). Arup's report has identified privacy, trust, and surveillance as crucial issues, emphasizing that obtaining people's consent and building trust is vital, particularly with the more widespread deployment of IoT technologies (Arup, 2019). This matter is particularly true in our CITYSTEPS's Stage 4, which starts containing human mobility data. Further challenges in terms of privacy include the fact that anonymized data may be combined with other sources, diminishing the level of privacy and potentially leading to identifying individuals (Narayanan & Shmatikov, 2008).

As one solution to protect privacy, Papyshev and Yarime (2021) propose a "task-based approach" to urban mobility data generation, where city authorities ask people to conduct certain activities to create synthetic data. Also, several frameworks have been developed to protect the identifiability of human mobility data (Savi et al., 2023). Among these frameworks, differential privacy is the leading approach to mathematically addressing the trade-off between privacy protection and utility for analysis and simulation. Differential privacy protects individual privacy while sharing information about a group of individuals by introducing randomness into a dataset without changing the eventual data analysis (Savi et al., 2023). Savi et al. (2023) demonstrate that differential privacy preserves individual privacy in human mobility data.

7.4. Participatory approaches

Participatory approaches have been found effective in bridging the gaps in CDTs. Nochta et al. (2021) highlight the need for a more nuanced conceptualization, design, and implementation. They find the need for prospective users to understand better the functionality and boundaries of CDTs in terms of opportunities, limitations, risks, and uncertainties. In contrast, providers or modelers of CDTs must engage with diverse stakeholders to design socially relevant and appropriate systems. Upon examining existing projects (see appendix), we find that citizens' public participation is somewhat limited, though several projects test public participation. There are some technical challenges in this domain. For example, digital twins entail high entry barriers regarding technical skills, and implementations may not be readily accessible. Capacity building is challenging even for practitioners, let alone the public.

7.5. Social inclusion

Research on AI and digital twin technology in other fields has highlighted potential risks for inequality and injustice (e.g., healthcare sector (Popa, van Hilten, Oosterkamp, & Bogaardt, 2021), sustainable development (Tzachor, Sabri, Richards, Rajabifard, & Acuto, 2022) and AI with algorithms (Zou & Schiebinger, 2018)). For instance, in the healthcare sector, it has been noted that the use of digital twin technology may exacerbate existing socio-economic disparities, both within a country and internationally (Lal, Dang, Nabzdyk, Gajic, & Herasevich, 2022; Popa et al., 2021). Additionally, Popa et al. (2021) has expressed concerns that existing biases may be exacerbated if digital twin technology is designed primarily from the perspective of the current majority population. These concerns are not limited to healthcare; the potential negative consequences of digital twin initiatives for cities also exist.

First, the current system is not able to effectively incorporate the digitally invisible population. For example, undocumented people (e.g., refugees, foreign nationals, homeless, and gig workers) and temporary visitors (e.g., tourists and business trip professionals) are not well recorded in official data (Milan & Treré, 2020). Milan and Treré (2020) discuss that during the pandemic, these invisible people are virtually absent in official data, leading to the following two consequences: the increase in risk for these invisible people and their surrounding communities; and the absence of support for these invisible people even in resource-rich countries. Examples include sex workers who are typically excluded from pandemic recovery plans as well as operations in informal sectors who can not be counted for unemployment subsidies (Milan & Treré, 2020). This invisibility problem of undocumented people or temporary visitors can happen in CDT. Those who are not in official data may not be recorded in CDT, resulting in the disappearance of simulations or planning scopes, and may not be considered when implementing the outcomes of the simulations in the real world.

In the case of CDT, the population to be covered by the technology is critical. However, it is not straightforward to incorporate this invisible population. Take the example of the homeless. The definition of homelessness is not standardized across countries, regions, and surveys. For instance, authorities in the Netherlands have not formally defined homelessness, but each municipality has the authority to determine the definition (Coumans, Cruyff, Van der Heijden, Wolf, & Schmeets, 2017). The homeless other than those living on the street and those using shelters (i.e., invisible homeless or hidden homeless) do not appear in the data as homeless. Deleu, Schrooten, and Hermans (2021) conducts a systematic review of hidden homelessness, finding that very little longitudinal study on hidden homelessness is available. They conclude that: i) there is no consensus regarding the definition of hidden homelessness, ii) most studies underestimate the number of hidden homeless, and iii) existing studies cannot capture the diverse profiles of hidden homeless people. Also, homeless people tend to change their place of residence and type of residence on a short-term basis, making it difficult to obtain accurate data on the latest situation. Homeless shelters close or relocate, depending on weather or economic conditions (B. A. Lee & Price ‐ Spratlen, 2004). Also, homeless people move to meet subsistence needs and respond to geographic changes in service delivery (B. A. Lee & Price ‐ Spratlen, 2004). A more visible but smaller share of the homeless population – called chronically homeless – experiences longer periods of homelessness or transits in and out of homelessness over several weeks, months, or years (OECD). On the other hand, a larger share of the homeless population is homeless for only a limited period before finding a more stable housing option (OECD). In addition, disasters or social disruptions suddenly increase the homeless population in a short period, making the official count more challenging (Haraguchi et al., 2022).

The same applies to seasonal workers or immigrants. For example, Fazel-Zarandi, Feinstein, and Kaplan (2018) claims that the number of undocumented immigrants tends to be underestimated for inflow and overestimated for outflow, analyzing more than 25 years of data in the United States. They find that undocumented immigrants are estimated to be nearly 50-200% higher than the prominent current estimate which is based on survey data.

We propose the following recommendations to ensure that CDTs evolve inclusively, reflecting advancements in fields such as AI and healthcare digital twins. The first is about *comprehensive and unbiased data collection*: One of the fundamental prerequisites for unbiased simulations and analyses in CDT is the collection of comprehensive and impartial data. Biases inherent to the data collection process often mirror entrenched and obscured prejudices embedded within institutional infrastructures and prevailing social power dynamics (Parmar, Leiponen, & Thomas, 2020; Zou & Schiebinger, 2018). Therefore, city authorities can enhance the inclusivity of their data by fostering collaborations with human rights organizations, legal entities, and city government offices, such as human rights and customs. This collaborative process can facilitate the seamless data collection from populations such as undocumented individuals without compromising their information. For short-term visitors, data acquisition can be streamlined through dedicated smartphone applications targeting tourists.

The second is about *transparency in data provenance*: Annotating data, especially data linked to individuals, with metadata detailing its collection methods is imperative. Such metadata should encompass demographic attributes, including geographic location, gender, ethnicity, race, and other pertinent information (Zou & Schiebinger, 2018).

The third concerns *vigilance against algorithmic biases*: As our Maturity Model progresses to Stages 7 and 8, encompassing autonomous reasoning and AI-driven decision-making, heightened scrutiny is required to detect and rectify biases. Algorithms, especially within the areas of machine learning and AI, must undergo rigorous validation to ensure their neutrality. Leveraging existing de-biasing techniques can aid this effort (Nazer et al., 2023; Varsha, 2023). To optimize the design and functionality of the CDT system, it is paramount that these recommendations are integrated from the outset—specifically at Stage 1, the planning phase of our CITYSTEPS Maturity Model. Instituting post-design changes can be cumbersome and compromise the system's holistic integrity.

8. Policy implications and regulatory frameworks

To effectively address the inherent challenges and to institute robust governance as CDTs evolve, it's essential to establish specific policy and regulatory frameworks. First, *human-centric design* is vital. At the core of CDT, human involvement remains indispensable. It ensures that human rights and values, such as solidarity, are upheld, particularly as we navigate the advanced stages of our Maturity Model characterized by autonomous systems reliant on AI and machine learning (Suffia, 2023). Such human oversight is crucial for our understanding of social dynamics and communication within urban spaces, nudging the design paradigm from a mechanistic "City as a Computer" towards a more organic "City as a Living Organism" (Suffia, 2023). Second, a *clear differentiation of boundaries and responsibilities* should be made. As we integrate diverse data sources and technologies, it becomes crucial to distinctly delineate responsibilities and establish clear boundaries. Third, an *adaptive regulatory framework* needs to be built. Given the dynamic nature of CDT, which continually evolves, regulatory frameworks must remain adaptive. Recognizing CDT as a complex adaptive system facilitates this agility (C. Liu & Tian, 2023).

Moreover, in areas with significant impacts, adopting precautionary principles becomes paramount. Such principles, traditionally applied to environmental and human health domains, enable policymakers to take preemptive action despite scientific uncertainty (Suffia, 2023). Lastly, these facets mentioned above—ensuring human involvement, setting clear boundaries, and designing an adaptive regulatory framework—should be planned in Stage 1 of our Maturity Model: Prioritization during the Planning Stage. Governance considerations and human factors should be deliberated before embarking on data collection and system integration. Our governance guidelines furnish a roadmap for discussions at this juncture (Yossef Ravid & Aharon-Gutman, 2023).

9. Prospects of CDTs

The promise and sustainable future of CDTs hinge upon their scalability and adaptability. Understanding these critical parameters is crucial to explore the long-term prospects of CDTs. One robust method to assess these features is the Global Innovation Systems framework by Binz and Truffer (2017), which provides insights into technological innovation processes. Central to this framework are two mechanisms: the multi-geographical resource generation dimension—spanning regional, national, transnational, and global scales—and product valuation dimensions, which encompass knowledge creation, financial investment, market formulation, legitimation, and structural couplings among stakeholders. Currently, some CDT projects demonstrate resource formulation at regional levels, as seen in Zurich and OnDejoin in France, national projects like Project PLATEAU in Japan, and EU's transnational initiatives such as DUET. However, a void persists on a global scale. While the academic and private sectors bolster knowledge creation through research and development, financial investment in CDTs has surged, mirroring the market's exponential growth over recent years. Governments back legitimation through their projects, yet, as discussed previously, there's a pressing need to amplify participatory approaches and social inclusion. Active structural couplings are underway, which is evident in consortium formations (e.g., Digital Twin Consortium). To ensure the sustainable evolution of CDTs, it's paramount to institute global mechanisms and standards, mainly focusing on interoperability and data integration. The engagement and inclusion of citizens and stakeholders stand central to the longevity of both the technology and urban development (Goel, Yadav, & Vishnoi, 2021). When projects incorporate the feedback of its citizens, their sustainability potential escalates.

The adaptability of CDTs intertwines with accountability and transparency. Initiatives that uphold these principles—like the DUET project, which underscores transparency by publicizing reports and manuals—can readily extend their models to other cities (See Supplementary Document). However, it's essential to note that CDTs, still nascent in their development, require ongoing evaluation concerning these sustainability-related features in future studies.

10. Conclusions

CDT represents an emerging technology in the realm of digital transformation. We assessed its technological and governance structures and our CITYSTEP Maturity model for CDT. These are aimed at our primary audience—planners, decision-makers, policymakers, and researchers—to explore present opportunities and challenges in-depth. The CDT not only offers the potential to enhance citizen participation in urban planning but also addresses issues in smart city development, such as creating a common information systems model, increased citizen engagement, and heightened community awareness.

However, several challenges remain, both socially and technically. Privacy concerns are vital to gaining the trust of citizens. Also, enhancing public participation needs to be encouraged more actively in the planning and implementation of CDT. Technical challenges, such as data integration and interoperability, should be addressed. Our research suggests that the CDT projects are less socially inclusive due to their dependence on available data fed into the digital twin platform. Currently, data collection methods, such as census and community surveys, do not fully capture marginalized populations, such as the hidden homeless, foreign immigrants, and seasonal workers, and may not be able to quickly respond to sudden changes in human mobility and population due to disruptions such as pandemics, disasters, or conflicts. New data sources, such as smartphones and open data from shared mobility, can potentially address these gaps as they can collect data on the ground more in real time (Haraguchi et al., 2022).

The CITYSTEPS Maturity model provides us with tools to transfer experiences in big cities to other small towns and non-urban areas, which is currently one of the vital urban issues discussed in the literature (Haraguchi, 2020; Pereira et al., 2023). Our model helps evaluate the current state, future directions, and the governance implications of the technology. By doing so, it helps stakeholders implement the technology more inclusively.

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Supplementary Document

1. Analysis of selected CDT initiatives: Overview

In this supplementary section, we compare the following CDT initiatives to find out what similarities and differences exist among different CDT initiatives. We analyze their published documents and relevant articles of the following five projects: i) Digital Twin and 3D models (DUET) in Flanders in Belgium, Pilsen in Czechia, and Athens in Greece, ii) The Digital Twin of the City of Zurich for Urban Planning in Zurich, Switzerland, iii) National Digital Twin program (NDTp) in the UK, iv) OnDijon in Dijon France, and v) 3D BAG in the Netherlands.

We have selected five projects for this study that encourage distinctive citizen participation at the planning or the implementation stages. In selecting these projects, we have also taken into account the differences in operational entities, including projects led by academia, municipalities, and private companies. By analyzing these diverse projects, we aim to examine how they address various aspects of CDT implementation, including data collection, sharing, and citizen participation among multiple stakeholders.

1.1. Objectives

To summarize the objectives of each project, NDTp focuses on data development and framework building (The Centre for Digital Built Britain), DUET focuses on data collection, simulation, policy making, and public participation (DUET, 2022b), and The Digital Twin of the City of Zurich for Urban Planning data collection, simulation and data publication (Schrotter & Hürzeler, 2020), OnDijon was for data collection (Dijon Metropole), and 3D BAG was for data collection and simulation (3D Geoinformation Research Group, 2022; Dukai et al., 2020).

Some projects have outcome-based objectives without specifying target outputs. For example, DUET stipulates its objectives: i) create a digital twin approach for collaborative policymaking, ii) test the DT approach for more effective policy implementation, and iii) ensure broader impacts through scalability and transferability.

In contrast, other projects include objectives with more specific target outputs. For example, The Digital Twin of the City of Zurich explicates its objective of using the 3D spatial data model in the city administration in the fields of environmental and urban planning or third parties for visualization of construction projects (Schrotter & Hürzeler, 2020). Furthermore, OnDijon in Dijon, France, has more concrete targets, such as achieving significant energy savings by installing LED lighting in 93% of the facilities, improving the security of public space, and developing better coordination in the event of crisis management (Dijon Metropole). Similarly, 3D BAG in the Netherlands has objectives to apply CDT to energy use in building, wind and pollutant simulation, noise pollution, and new projects’ evaluation (3D Geoinformation Research Group, 2022; Dukai et al., 2020).

1.2. Data Types and collection

By purpose, in terms of data collection, NDTp and DUET focus on environmental data such as road traffic information, air pollution data, thermal environmental data, and noise data. On the other hand, Zurich’s project and 3D BAG collect geographic information such as topographic data and aerial imagery. OnDijon collect data on the current state of the city's infrastructure, such as traffic conditions, street lighting data, and security camera video data.

Human mobility data is a critical data source for city digital twin technology, allowing for the dynamic nature of cities to be accounted for (Haraguchi et al., 2022). Historically, this type of data has been gathered through methods such as national census, trip surveys, transportation data, and travel surveys. However, more recently, new IoT data sources, including smartphones and the General Transit Feed Specification (a geospatial information format for public transport), have also been used to collect human mobility data (Haraguchi et al., 2022; Nishino et al., 2021). This data can then be input into the city digital twin.

Conversely, city digital twin technology provides various opportunities for city planners to analyze and simulate human mobility in new ways. Previously, simulation of human mobility has been achieved through techniques such as machine learning and ABM (Haraguchi et al., 2022). However, these techniques were often limited to specific technical environments or scenarios. In contrast, city digital twin technology enables a higher granular simulation of human mobility by combining data from various sources, such as buildings, roads, and the environment (Mendula, Bujari, Foschini, & Bellavista, 2022). This provides planners with broader, richer opportunities to analyze and simulate human mobility in a much more comprehensive way.

DUET and OnDijon have created models of human mobility data using road traffic information (DUET, 2022; Metropole). In particular, DUET conducts simulations using this model and combines analysis with other simulation data in order to make decisions and policies on environmental issues such as pollution (crisis management analysis) (DUET, 30 September 2021).

1.3. Target Areas

Target areas and purposes differ among these projects. For example, the DUET uses simulation results to collect public comments and to aid in policy making (DUET, 30 September 2021, 2020). On the other hand, Zurich's project aims to raise awareness of disaster prevention and pollution control by disclosing simulation data to the public (Schrotter & Hürzeler, 2020), and the 3D BAG used simulation data for research and development (3D Geoinformation Research Group, 2022; Dukai et al., 2020).

Comparing the plans of each project, NDTp, DUET, The Digital Twin of the City of Zurich for Urban Planning, and 3D BAG mainly analyze urban structures to contribute to environmental issues such as energy consumption and air pollution, as well as urban planning, while OnDijon aims to improve citizen services. OnDijon was designed to improve citizen services, focusing on real-world problems (short-term problem solving) (Dijon Metropole).

1.4. Developers and Stakeholders

Various actors develop CDT by collaborating with multiple actors. The first type of project is the one developed and initiated by the public sector. For example, Zurich's project is led by the GIS City of Zurich (GIS Stadt Zurich) and implemented with the partners such as 25 service departments of the City of Zurich ETH Zürich, Fachhochschule Nordwestschweiz (Schrotter & Hürzeler, 2020). The data is provided by utility and communication companies. The second type is the project led by academia. 3D BAG in the Netherlands is developed by the Delft University of Technology (3D Geoinformation Research Group, 2022; Dukai et al., 2020). The last type is a joint initiative or consortium of public and private sectors and academia. For instance, OnDijon in France is an initiative of 23 municipalities, consulting company, an energy and energy infrastructure company, and a water and waste management company (Dijon Metropole). Other examples include NDTp in the UK, which is jointly led by Department for Business, Energy & Industrial Strategy, government of UK and the University of Cambridge, and Flanders in DUET (public and academia), and Athens in DUET (private and NPO sectors).

Citizens play an essential role in some projects, making the projects more participatory and democratic. DUET, Zurich's project and Ondijon, where the government plays a central role in development, promotes citizen participation in developing the technology and in using the technology through the development of games and apps. For example, the Ondijon project employs a smartphone app-based mechanism that links citizen-generated data to a digital model, facilitating citizen participation as information providers. Ondijon scores high in terms of citizen participation during the implementation stage. However, some critics argue that the project failed to achieve its goals due to the insufficiently inclusive citizen participation during the planning stage (Nicolas, Kim, & Chi, 2020). In contrast, DUET collects public opinion at the planning stage using a specified method (i.e., an agile methodology (DUET, 20 July 2020).

1.5. Dynamic models

Some CDT initiatives develop a spatially, temporarily dynamic model: variable data, such as traffic, air quality, and noise, are modeled with a time component, in addition to the constant factors such as topography and buildings. In the three projects NDTp, DUET, and OnDijon, 3D digitization of dynamic models, including electricity usage and traffic conditions, is being promoted (Dijon Metropole; DUET, 2022b; The Centre for Digital Built Britain). On the other hand, Zurich's project and 3D BAG are mainly concerned with the 3D digitization of permanent elements such as topography and buildings (3D Geoinformation Research Group, 2022; Dukai et al., 2020; Schrotter & Hürzeler, 2020).

1.6. Challenges and issues identified by the developers

The projects DUET and OnDijon, which focus on the creation of dynamic models, have identified challenges related to social aspects such as finding common ground between creators and users, and reconciling the need for open data with the protection of personal information. Conversely, the projects Zurich and 3D BAG, which do not utilize dynamic models, have primarily encountered technical difficulties, such as the integration and acquisition of data.

In the development of dynamic models, both technical and social challenges must be considered. These include balancing the protection of personal information with the promotion of open data, and achieving consensus among stakeholders. Additionally, it is important to recognize that current data collection methods may result in bias and overlook important population segments, such as undocumented individuals. This could further exacerbate existing urban issues, such as urban segregation, if not addressed properly, resulting in "digital" urban segregation. The significance of these social challenges will be discussed further in Section 6.

1.7. Their maturity model

3D BAG leverages a maturity model to assess the level of detail in its 3D dataset. However, among the five projects analyzed, only DUET implemented a comprehensive maturity model throughout its project.

Table S-4: Objectives, stakeholders, and data providers of selected CDT projects in European countries

Project	Country /City	Data type and collection	Dimension	Target areas	Developers and stakeholders	Challenges identified by developers	Source
The National Digital Twin program (NDTp)	UK	Sensors installed in buildings, infrastructure	3D	Energy consumption occupation Air pollution Traffic information (flow, volume, speed, route)	CDBB (Department for Business, Energy & Industrial Strategy, government of UK and the University of Cambridge)	Data maintenance, Building a framework	The Centre for Digital Built Britain
DIGITAL URBAN EUROPEAN TWINS (DUET)	Flanders, Belgium	Geographic information (2D model), road traffic information, public transportation operation information, air pollution information	3D	Traffic regulation, environmental assessment	Digitaal Vlaanderen （Government） imec（Academia）	Information gathering, simulation, policy making, public participation	DUET (2022b)
	Pilsen, Czechia	Geographic information (3D building model), road traffic information, public transportation operation information, air pollution information, thermal information, noise	3D	Traffic information (traffic volume, vehicle type, speed limit), noise, city planning	City of Pilsen （Municipality）	Information gathering, simulation, policy making	DUET (2022b)
	Athens, Greece	Geographic information, road traffic information, public transportation operation information, air pollution information	3D	Traffic information, health, environmental policy	DEMO (IT company） GFOSS(NPO in ICT）	Information gathering, simulation, policy making, public participation	DUET (2022b)
The Digital Twin of the City of Zurich for Urban Planning	Zurich, Switzerland	Terrain model acquired by LiDAR, floor plan by land survey, roof shape record by aerial photogrammetry	2D ~3D	Urban planning, evaluation of real estate planning, simulation of noise, flooding, etc.	the City of Zurich （municipality）	Data collection, simulation, Data disclosure	Schrotter and Hürzeler (2020)
OnDijon	Dijon, France	Transportation, infrastructure information, street lights, security cameras	3D	Centralized management of citizen services such as transportation and	Dijon Métropole （municipality）	Data collection	Dijon Metropole

				infrastructure by remote control			
3D BAG	Netherlands	Height information acquired by LiDAR, data set on terrain records	2D ~3D	Energy consumption, air pollution, noise, Analysis of urban structure	3D geoinformation research group part of the Delft University of Technology	Data collection, simulation	3D Geoinformation Research Group (2022); Dukai et al. (2020)

Table S-5: The CDT development evaluated by our maturity model and governance (i.e. transparency, accountability, inclusion and participation).

Project name	Location	Maturity levels	Governance					
			Transparency		Accountability		Inclusion	Participation
Subcomponents			Planning documents	Data access	Reporting documents	Privacy guidelines and standards		
The National Digital Twin program (NDTp)	UK	6	✓ DBB level 3 Strategic Plan was announced in 2015. (Cambridge Living Laboratory Research Facility, 2022)	∆ Available only to those who have offices in the case study buildings.	✓ 9 reports were published.	✓ An attribute-based access control (ABAC) approach is recommended. (Kendall, 2021)	No	✓ Interviews and workshops were conducted during the planning phase to collect public opinions. (Nochta et al., 2021)
DIGITAL URBAN EUROPEAN TWINS (DUET)	EU	6	✓ 5 planning documents were published.	✓	✓ 3-year pilot project is implemented since 2020 and 38 reports were published.	✓Legal Landscape and Requirements Plan, Privacy Impact Assessments (PIAs)	Limited	✓ Interviews were conducted during the planning and application phases to collect public opinions.
The Digital Twin of the City of Zurich	Zurich, Switzerland	5	? (We could not find any info)	Free license since 2012 and Since 2018 the	∆ (Manuals are published)	Open government data policy	No	✓

for Urban Planning				data of the 3D city model has been available free of charge and for free use as a part of Open Government Data policy. (Schrotter & Hürzeler, 2020; The City of Zurich, 2023)		exists(Schrotter & Hürzeler, 2020)		Participation through game was made during the application phase to collect feedback.
OnDijon	Dijon, France	4	? (We could not find any info)	✓ App is available.	? (We could not find any info)	-Follow the General Data Protection Regulation (GDPR) -Establishing an ethics and data governance committee	No	✓ Citizens provided data through smartphone app in the application phase.
3D BAG	Netherlands	3	? (We could not find any info)	✓ Licensed under CC BY 4.0	? (We could not find any info)	✓ The CDT does not contain personal information.	NO	✓ Citizens provided feedback on model use in the application phase.
Note: ✓indicates a project has the respective function. x indicates that a project does not have the function. Finally, ? indicates it was not possible for us to judge if the function is already installed or not. All are as of April 30th, 2023.								

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