# Can Urban Digital Twins Support the Realization of Sustainable Development Goal 11? Identifying Key Social and Technical Challenges

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**Abstract**

The rapid urbanization of cities presents significant sustainability challenges, necessitating big data and digital tools as solutions for efficient resource management. A key advancement in this area is the Urban Digital Twin (UDT). UDTs aim to create dynamic virtual replicas of urban environments, enabling informed decision-making for city planners and policymakers. UDTs enable predictive modeling, resource optimization, and impact assessment of urban interventions. On the other hand, one of the globally accepted sustainable development goals (SDGs) to achieve by 2030 is SDG 11, which focuses specifically on "Sustainable Cities and Communities". SDGs and SDG 11 consider the cities as a system that consists of the physical urban environment and social dynamics coming from governance, citizens and communities. However, current research on UDTs has primarily focused on technical aspects, leaving the potential of UDTs to support SDG 11 and its social dynamics underexplored. This study aims to understand whether UDTs can support the realization of SDG 11. Therefore, we explore how the capabilities of UDTs, such as monitoring, modelling and simulation, visualization, information provision and collection can support the SDG 11 principles of managing interconnected targets, inclusivity, multi-stakeholder collaboration, and monitoring of SDG 11 targets. We propose a socio-technical framework illustrating how UDTs can support SDG 11 and outline the key social and technical challenges to be addressed to fully realize UDTs' potential. Finally, we discuss the conclusions and outlook for overcoming such challenges.

## 1. Introduction

In response to the challenges of rapid urbanization and with the aim of supporting the smart development of cities, the concept of Urban Digital Twin (UDT) and its applications have emerged as a powerful instrument in the domain of smart cities (Qian et al., 2024; Deren et al., 2021). 'Digital twin' term, coined by Grieves (2014), pertains to digital replicas of physical entities that run digital simulation models combined with real-time physical processes in question. A consensus emerging from subsequent studies (Grieves and Vickers, 2017; Zheng et al., 2019) posits that a digital twin enables two-way interaction between the virtual representations of physical entities and their real-world counterparts while enabling (real-time) data exchange, modelling, and simulations. These functionalities support decision-making by elucidating insights into the current state of the physical entity, predicting its future state, and optimizing associated processes (Lei et al., 2023).

UDT is the realization of the digital twin concept to urban areas and the city scale. Similarly to the original concept, UDTs are the virtual replicas of technical processes in cities (i.e., physical assets, landscapes), however, unlike the original concept, UDTs should also involve the social processes (i.e., human behaviour and activities) to fully represent a city (Batty, 2018; Marçal Russo et al., 2025; Abdelrahman, 2025). Moreover, UDT is seen as a strategic technology owing to its capacity both for short- and long-term evidence-based decision-making (Augustine, 2020). UDTs possess the ability to leverage data for monitoring various urban processes; to utilize simulation models for predicting future states of urban areas, and the so-called "what-if" scenarios to test the consequences of possible urban interventions; and to present the resulting insights for enabling decision support (Charitonidou, 2020). For instance, UDTs have been employed to assess the impact of planned construction projects (Lei et al., 2023) as well as to anticipate potential outcomes of disastrous events (Ford and Wolf, 2020). Although the use cases of UDTs differ, their primary function is to facilitate decision-making processes in the complex dynamics of urban environments (Coenen et al., 2021), and ultimately lead decision-makers to determine optimal solutions in a cost-effective manner for sustainable urban planning.

In recent years, UDT has garnered significant attention among experts in smart city research and practice (Wang et al., 2023; Weil, 2023). While UDTs, in principle, have the potential to encapsulate the complexities of interconnected urban processes (Batty, 2018), thereby supporting sustainability goals and decision-making (Park et al., 2019), the current research discourse primarily adopts a technology-driven and technocratic perspective such as the provision of realistic 3D visualization, the use of big data analytics, and the advancement of automation (Azadi et al., 2025; Nochta et al., 2021). Consequently, to what extent the existing UDT implementations can contribute to the sustainability of cities, not only from a technical perspective but also from a social one, remains unclear and not analysed thoroughly.

On the other hand, "Transforming Our World: the 2030 Agenda for Sustainable Development" which serves as a global guiding international framework for sustainable development efforts, was accepted by the United Nations in 2015 (United Nations, 2015). This agenda comprises 17 sustainable development goals (SDGs) for tackling climate change and protecting nature reserves while improving well-being and education, reducing inequality, and stimulating economic growth. These 17 SDGs are operationalized with 169 targets and 244 indicators which need to be supported by relevant data and monitoring from across the globe.

One particular SDG, SDG 11, focuses specifically on "Sustainable Cities and Communities". However, the progress of achieving the 2030 targets for SDG 11 has been globally stagnant since 2020 (Sachs et al., 2024). There are a few studies

(Hassani et al., 2022; Tzachor, 2022) that explain the possibilities of UDTs' contribution to achieving overall sustainability goals. While the general potential of UDTs in supporting sustainability goals have been discussed, research providing a comprehensive and structured overview of whether UDT can contribute specifically to SDG 11 remains scarce. Therefore, this study aims to explain and develop a systematic framework on how UDTs can support the realization of SDGs, specifically SDG 11 principles, across the dimensions including technical considerations, systemic management, strategic governance, and social collaborations. By moving beyond a purely technological lens, we explore how UDTs can serve as integrated tools for managing interconnected targets, promoting inclusivity and multi-stakeholder collaboration, and enabling monitoring of sustainability targets in cities. Furthermore, we identify the key challenges and limitations associated with leveraging UDTs for SDG 11.

## 2. Background

### 2.1 Urban Digital Twins

In recent years, UDTs have gained recognition as a promising solution to address sustainability challenges (Hassani et al., 2022; Tzachor et al., 2022; Fan et al., 2018), especially in urban planning processes, where UDTs support decision-making through analysis, simulations, and participatory practices (Tija and Coetzee, 2022; Charitonidou, 2022; White et al., 2021). Although UDTs are acknowledged for their unique capability of providing a comprehensive representation of reality, not all UDTs demonstrate the same level of comprehensiveness (Haraguchi et al., 2024; Masoumi et al., 2023). Therefore, several maturity level frameworks are developed (Haraguchi et al., 2024), such as DUET framework (DUET, 2024). On the lowest end of the UDT maturity level is the strategy phase where there is a political awareness and desire to create a UDT for decision-making. On the highest end is the future-ready phase where there is an intelligent UDT that can make predictions and simulations for real-time operation decisions.

A common ground in the literature for an implementation-ready "ideal" UDT, which we will adopt for this research, is that it utilizes 3D representations of urban environments, while seamlessly and holistically integrating diverse urban data sources and models -both coming from human and non-human entities-, employing real-time monitoring, modelling and simulation (what-if scenarios) capabilities, and enabling collaborative decision-making (Abdelrahman et al., 2025; Haraguchi et al., 2024; Masoumi et al., 2023). Inherently, UDTs allow visualization, information provision and collection. A UDT with such capabilities can reflect the dynamic nature and complexity of cities as socio-technical systems (Abdelrahman et al., 2025; Coenen et al., 2021; Nochta et al., 2021; Batty, 2018).

### 2.2 Sustainable Development Goals and Goal 11

By addressing economic, social, and environmental challenges simultaneously, the SDGs promote a holistic and integrated approach toward a *more prosperous, inclusive, just, and environmentally responsible world* (Fabrizio et al., 2015). Each SDG has specific targets and indicators to track global progress toward 2030. The global challenges that SDGs address are interconnected and interdependent (Le Blanc, 2015; Pham-Truffert et al., 2020). Thus, each of the 17 SDGs as well as **targets of each SDGs are interconnected** (United Nations, 2013), meaning action on one target would affect others. This interconnectedness requires active management. The SDGs are also universal, grounded in **inclusivity** and "leaving no one behind", aiming to improve the well-being for all (Gupta and Vegelin, 2023).

One of the emphases of the SDGs is the need for collaboration among diverse stakeholders (Andreoni, 2020). Global Sustainable Development Report (United Nations, 2023) highlights the need for **multi-stakeholder collaboration** between governments, businesses, civil society, and individual actors across disciplines and regions to cultivate trust and build a strong scientific foundation for achieving the SDGs. With the 2030 deadline approaching (United Nations, 2015), tracking progress and identifying gaps is crucial. For that purpose, a **regular monitoring via data, and reporting mechanisms help track SDG targets** (Fraisl et al., 2020; United Nations, 2015).

Within the 17 goals, **SDG 11 specifically focuses on making cities and urban settlements inclusive, safe, resilient, and sustainable**, highlighting its role in global development. SDG 11 addresses major challenges in cities and communities that include housing shortages, the rise of slums; urban sprawl and its detrimental effects on land; urban residents' lack of convenient access to public transport; insufficient dedicated area for open public spaces and streets; the poor air quality in cities and towns; and the lack of quality infrastructure which is especially needed for developing and implementing local disaster risk reduction strategies and the lack of public engagement in decision-making (United Nations, 2023; 2015).

UDTs present the potential to support SDG 11 targets through their application on various use cases such as accessibility to facilities, monitoring resources, disaster management, and community engagement and participation, separately or integratively (Patel et al., 2024; Hassani et al., 2022; Tzachor et al., 2022). In Table 1, we show SDG 11 targets, their attention areas and examples from the existing literature focusing on UDT use cases related to the SDG 11 targets.

As the inherent aims of SDGs reflect, supporting SDG 11 targets is not only about focusing on a certain use case. Based on the literature and arguments above, we can conclude on 4 principles to achieve SDGs and specifically SDG 11 targets on "sustainability of cities and communities": (i) management of interconnected targets, (ii) inclusivity, (iii) multi-stakeholder collaboration and (iv) monitoring of SDG targets. Below, we will first explain these aspects and then elaborate on how "an ideal" UDT can support these principles.

## 3. How can UDTs support the realization of SDG 11?

### 3.1 Management of Interconnected Targets

While each SDG 11 target addresses a specific challenge in cities, they are interrelated, and progress in one target can have cascading effects across others, as in any complex system (Collste et al., 2017). For instance, improving public transport can increase housing demand in well-connected areas, influencing housing prices and urban development patterns. Recognizing these interconnections calls for integrated, cross-sectoral management strategies, which traditional siloed approaches often miss (Bai et al., 2016).

Malleson et al. (2024) suggest that UDTs can bridge this gap by **modelling and simulating**, and **monitoring** sectoral interdependencies. Because UDTs can seamlessly connect diverse urban data sources and the modeling algorithms relevant to different urban planning sectors, offering a comprehensive

view of urban development over various time horizons (i.e.; short, medium, and long-term planning) (Coenen et al., 2021).

| SDG 11 Target[a] | Attention Areas | Potential UDT Use Case |
|---|---|---|
| 11.1 | Monitoring urban population in slums | Assessing accessibility of housing and basic service, e.g.:Implementing human-centric infrastructure resilience (Ye et al., 2023) |
| 11.2 | Accessibility of vulnerable people | Transport systems management and planning e.g.: Modelling of intelligent transportation infrastructure (Gao et al, 2021) |
| 11.3 | Monitoring land consumption; Participatory urban planning | Participatory, integrated, and sustainable planning and management e.g.: As platform for participatory decision-making (Tartia and Hämäläinen, 2024; Dembski et al., 2020; Fan et al., 2021; Hämäläinen, 2021; Schrotter and Hürzeler, 2020) |
| 11.4 | NA | Cultural and natural heritage management through digital models (Hutson et al., 2023) |
| 11.5 | Monitoring population affected by disasters; Monitoring critical infrastructure and disruption to basic services | Disaster and risk management, e.g.: Community disaster management (Tartia and Hämäläinen, 2024; New South Wales Digital Twin, 2025; Ford and Wolf, 2020) |
| 11.6 | Monitoring waste; Monitoring air quality | Environmental impact management, e.g.: As platform for multi-stakeholder waste management (Cardenas-Leon et al., 2024) |
| 11.7 | Accessibility; Safety; Inclusivity (Vulnerable people); Monitoring public spaces | Green and public spaces management, e.g.: Enhancing walkability through a green pedestrian network (Hämäläinen, 2021; Gholami et al, 2022) |

Table 1. Attention areas and potential UDT use cases for SDG 11 targets[a]. [a] https://www.globalgoals.org/goals/11-sustainable-cities-and-communities/

Although existing UDTs such as Zurich (Schrotter and Hürzeler, 2020), Kalasatama (Hämäläinen, 2021) and NWS Digital Twin (2025), cover several SDG 11 targets through use cases, there is not yet one UDT that can cover all SDG 11 targets in an integrated way. To operationalize UDTs for the management of interconnected targets, it is crucial to define what will be assessed and to determine the necessary data and models for monitoring. This may require developing an **integrated impact assessment framework** before UDT creation (Azadi et al., 2025; Batty and Yang, 2022). Additionally, successful implementation depends on **holistic data and model integration and continuous monitoring**, which also require **a robust data infrastructure** (Hämäläinen, 2021).

### 3.2 Inclusivity

In inclusive cities, all citizens, including marginalized groups, should have equal access to basic services, urban spaces, and economic opportunities, and participate in civic life (Elias, 2020; van Gils and Bailey, 2021). As highlighted in SDG 11, particularly SDG 11.2, 11.3 and 11.7 (see Table 1), accessibility, safety, and inclusion of (vulnerable) people are key with a strong emphasis on participatory planning practices which is a fundamental element of sustainability (Kleinhans et al., 2022). UDTs can enhance inclusivity by empowering citizens to participate in decision- making (Dembski et al., 2020) through open data and digital twin platforms (Charitonidou, 2022; Lei et al., 2023). By integrating diverse data sources, UDTs provide a comprehensive view of urban dynamics, enabling the **monitoring of current and future risks** (Tzachor et al., 2022). Up-to-date and big open data can facilitate accuracy, transparency, and inclusivity in decisions by possibly covering the needs of different segments of populations.

Open UDT platforms, through their **visualization and information provision and collection capabilities**, support local communities with participatory tools (i.e.; scenario planning and visualization through virtual reality applications, such as in Herrenberg (Dembski et al., 2020), serious games such as in Zurich (Fan et al., 2021; Schrotter and Hurzeler, 2020), public participation GIS such as in Kalasatama (Hämäläinen, 2021)), enabling citizens to understand and contribute to urban plans. As such, citizens can become part of the decision-making processes while also accessing open data and platforms that allow them to ask their relevant questions and even develop further open data-driven innovation projects (Kassen, 2013; Tzachor et al., 2022; Seto et al., 2023).

Overall, open UDT frameworks provide replicable and universal solutions (Raes et al., 2022). They can activate the **collaborative and transparent decision-making capabilities** of UDTs by incorporating diverse societal perspectives and prioritizing the needs of various population groups.

### 3.3 Multi-stakeholder collaboration

Multi-stakeholder collaboration is suggested to span various disciplines, agencies, government levels, and geographical contexts for achieving SDGs (Tzachor et al., 2022). Particularly for SDG 11, multi-stakeholder collaboration is crucial for inclusive decision-making in cities. Effective collaboration entails sharing knowledge, resources, addressing urban challenges at multi-scales, and effectively disseminating research and policy outcomes (Nonet et al., 2022). UDTs can support SDG 11 by enabling multi-stakeholder collaboration and stakeholder engagement (Mark Allan and Foliente, 2024). This can be in two ways: (i) facilitating co-creation and (ii) establishing workflows between a variety of groups (Lei et al., 2023), by **aggregating a wide array of data from different disciplines, modalities, and scales** into a unified platform, and **enabling communication and dissemination among project stakeholders**. Additionally, the **integration of cloud**

**computing technology** further enhances this collaboration by **facilitating analysis, simulations, and visualizations in a shared platform**, regardless of the geographical distances among project partners (Tzachor et al., 2022). The possibility of sharing a large amount of data and information on the cloud with multiple stakeholders from different institutes enables collaborative and evidence-based decision-making. A notable example is the Kera UDT from Espoo, Finland, which aids climate adaptive urban renewal by supporting stakeholders throughout the planning process (Tartia and Hämäläinen, 2024). This study underscores the ned for a socio-technical perspective in UDT development and integrating collaborative models/frameworks from social sciences into UDT development for better multi-stakeholder collaboration.

### 3.4 Monitoring of SDG 11 Targets

Benchmarking and monitoring the changes over time within (and between) cities facilitate data-driven decision-making on new policies and interventions (Giles-Corti et al., 2020), leading to effective implementation of the SDG 11 targets. UDTs can **monitor urban areas from different perspectives** by using diverse data sources. For instance, the availability of sensors and IoT data can help monitor moving objects and humans (Lehtola et al., 2022) and also urban health dimensions such as waste (Cardenas-Leon et al., 2024). Moreover, remote sensing data can support the monitoring of land consumption in time, detecting informal settlements (Tjia and Coetzee, 2022), or the monitoring of affected areas during disasters by comparing before and after images (Fan et al; 2021); volunteered geographic information (VGI) and social media data can help monitor the use of public spaces (Chen et al., 2018). Additionally, **visualization, information provision and collection capabilities of UDTs can facilitate communication and reporting of information more understandably** for a variety of stakeholders.

Overall, grounding on existing literature, we elaborated on the capabilities and requirements of an "ideal" UDT to support SDG 11. The summary of this literature synthesis and discussion is outlined in Figure 1, representing how UDT can support the SDG 11 "Sustainable Cities and Communities" principles, particularly focusing on the social processes involved. While technical considerations such as open data, open platforms, and a robust IT infrastructure remain fundamental (as represented by the elements surrounding the UDT core), UDTs can also play a crucial role in systemic management and strategic governance, enabling integrated impact assessments, benchmarking and reporting mechanisms, and addressing use cases relevant to SDG 11 targets (as presented in the light blue area). Furthermore, UDTs facilitate social inclusion and collaboration by integrating open participatory tools and supporting the development of technical and social frameworks that encourage multi-stakeholder collaboration. These dimensions highlight that achieving SDG 11 principles with the support of UDTs requires not only technological advancements but also integration of multiple social processes. In the next section, we will discuss the challenges and limitations associated with maximizing the potential of UDTs to realize SDG 11.

## 4. Challenges for UDTs to Support SDG 11

Most UDT applications in the literature focus on individual research area, such as energy, transportation, or infrastructure in isolation. Masoumi et al. (2023) highlight the lack of variety and interconnectedness in UDT use cases, advocating for a more integrative and systematic approach to designing UDTs to support the sustainability of cities in line with the SDG principles. One main challenge for having an integrative and systematic approach is to recognize UDTs as socio-technical innovations shaped by both technical advancements and social processes, rather than a purely technical tool, similar to other smart city technologies (Jiang et al., 2022; Nochta et al., 2021).

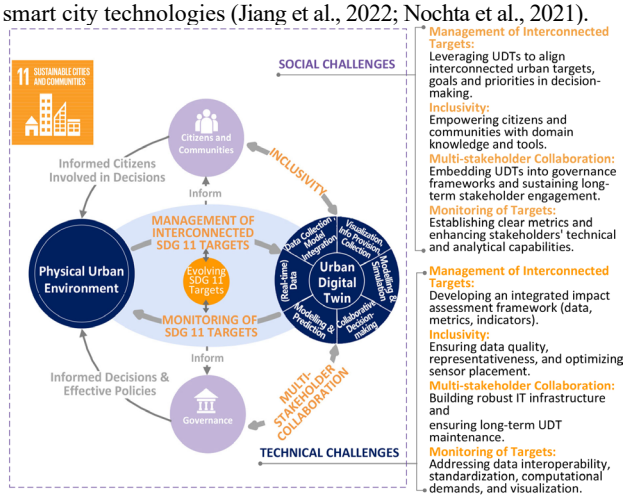


Figure 1. How UDT can support the SDG 11 principles and associated social and technical challenges

Currently, social processes are absent in UDTs because UDTs are seen mostly as technical innovations. This oversight hampers their ability to address the broad, interconnected needs of sustainable urban development, especially concerning citizens, communities, and governance dynamics. Thus, alongside technical challenges, social challenges are critical for the effective deployment of UDTs. Figure 1 summarizes these dual-perspective challenges within the UDT-SDG 11 system, and the challenges will be further examined across the four SDG 11 principles in the following discussion.

### 4.1 Challenges for Management of Interconnected Targets

UDTs aid stakeholder decision-making through "what-if" scenario analysis. When decisions involve multiple interconnected targets across different domains, the complexity increases, requiring a holistic view such as building UDTs based on an integrated impact assessment framework (Lohman et al., 2023). A technical challenge is developing UDT components, data, simulation models, and visualization systems in alignment with the framework's requirements (i.e., data, metrics, indicators) (Batty and Yang, 2022). This creates the necessity for a tailored approach while developing UDTs, rather than using off-the-shelf tools. This requires collaboration among decision-makers, urban planning domain experts (giving input for social processes), and system and hardware engineers (giving input on data, technology and techniques for UDTs) throughout the development process of UDTs (Nochta et al., 2021). Thus, they can collaboratively decide which social and technical targets and indicators are needed for well-informed decision-making. However, this also represents a social challenge as stated in previous studies and UDT implementations (Marçal Russo et al., 2025; Azadi et al., 2025; Nochta et al., 2021; Tartia and Hämäläinen, 2024).

### 4.2 Challenges for Inclusivity

Achieving inclusivity through UDTs is challenging, as representing all citizens and communities in UDTs requires human-generated data and the use of sensor networks, and also the use of UDT-based participatory tools. Looking at human-

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generated data such as VGI and crowdsourced data, it is often seen that such data quality suffer from human errors and lack of sensor calibration, as well as lack of representativeness of diverse population groups (Ferré-Bigorra et al., 2022). Additionally, sensor measurements are typically concentrated in densely populated areas like city centers, and more engaged citizens contribute disproportionately, leading to biased datasets and inclusivity issues for urban planning decisions (Robinson et al., 2022). As such, these issues create technical challenges for representing social processes in cities.

Integrating open participatory tools into UDTs to support inclusive cities requires also incorporating social processes. Common challenges with digital participation tools include (i) unreliable user-generated content due to limited domain knowledge, (ii) social exclusion due to complex technologies, and (iii) difficulties in facilitating meaningful and engaging discussion with citizens due to the complexity of outputs of the digital tools (Dane et al., 2024; Pfeffer et al., 2013). It is not that different for newly emerging UDT-based participation tools. Here the usual challenge is a good representation of a local community in the design of tools, which is necessary to enhance the usability, inclusivity, and accessibility of these tools.

### 4.3 Challenges for Multi-stakeholder Collaboration

In multi-stakeholder collaboration, several challenges arise that can hinder the effective integration of diverse stakeholders into a unified decision-making process through UDTs. To enable co-creation, collaboration and seamless workflows, it is necessary to align the differing agendas, technical capacities, and expectations of various stakeholders, from government agencies and urban planners to community groups and private sector partners. This diversity can lead to communication barriers, especially when technical jargon or complex data representations are involved (Nochta et al., 2021) or when there is no clear understanding of the necessity of UDTs in decision-making. This results in a social challenge of integrating UDTs into governance and policies while sustaining the engagement and awareness of all stakeholders for UDT development and utilization (Goodchild et al., 2024). This involves overcoming regulatory barriers and mitigating institutional resistance. Existing laws and regulations may not be well-suited to accommodate the requirements of UDTs, necessitating the creation or updating of policies related to privacy, ethics, and data security (Tzachor et al., 2022). Additionally, institutional resistance can arise due to bureaucratic disinterest or fear of losing control of decision-making (Tzachor et al., 2022).

Moreover, supporting co-creation and establishing workflows for collaborations might result in a technical challenge of collaborative platforms. Collaborative technologies such as cloud solutions rely on a robust IT infrastructure to enable cities to deal with sustainability challenges. However, developing a powerful IT infrastructure demands substantial investments in technology, infrastructure, and human resources (Tzachor et al., 2022). Ensuring that the IT infrastructure remains performant and responsive as the scale of the UDT expands presents a significant challenge, particularly concerning the long-term maintenance of UDTs. Ongoing efforts to secure funding and update technology are needed.

### 4.4 Challenges for Monitoring of SDG 11 Targets

“Benchmarking and reporting” is a crucial approach for monitoring and communicating the cities and/or urban areas’ performance on SDGs and for detecting the inequalities between urban areas. One major challenge is to define measurable metrics aligned with SDG 11 targets and ensuring data sets are consistent and comparable across cities or urban areas (Batty and Yang, 2022). Additionally, complex data and insights must be reported in ways all stakeholders can understand, therefore intuitive visual representations are necessary. Also, capacity building for improving stakeholders’ technical and analytical skills is important to increase their understanding of data and insights coming from UDTs.

Open-source databases and platforms are essential for data collection and provision in UDTs, especially for real-time monitoring. Cities like Zurich (Schrotter and Hurzeler, 2020) and Herrenberg (Dembski et al., 2020) have successfully leveraged open-source databases and platforms for UDTs, but interoperability remains a challenge due to diverse data formats and standards (Goodchild et al., 2024). Such open data is often stored in different systems and platforms that are inherently incompatible. Open data quality can vary greatly in accuracy, completeness, and timeliness.

Implementing real-time data monitoring, modeling and simulation tools in UDTs to deal with vast amounts of urban data and report meaningful insights necessitates significant technical expertise and computational resources. For instance, mapping and real-time monitoring of cultural and natural heritage sites and tracking urban resource consumption and waste demand advanced sensors, continuous updates and data analytics (Cardenas-Leon et al. 2024; Hutson et al., 2023).

## 5. Conclusion and Outlook

As an emerging technology, UDTs present potential to support SDG 11 by integrating capabilities such as data-driven decision-making, simulation, and participatory tools into urban management and planning. These capabilities enable cities to manage interconnected sustainability targets, inclusivity in urban decision-making, multi-stakeholder collaboration, and monitoring of sustainability targets. However, realizing these benefits requires careful integration of UDTs into urban governance frameworks, ensuring that their deployment considers the local social and spatial context while addressing both technical feasibility and societal impact (Jiang et al., 2022).

While UDTs offer promising solutions for sustainable urban development, their implementation is hindered by several interconnected social and technical challenges. From a systemic perspective, current SDG 11 targets and its indicators are often vague and open to interpretation. Therefore, more explanatory SDG 11 targets and measurable indicators are necessary (Schweiger, 2016) to develop integrated impact assessment frameworks that reflect the evolving realities of urban systems. Moreover, cities must move beyond siloed planning approaches and adopt integrated strategies that address multiple urban goals concurrently, recognizing the interdependencies among housing, transportation, green space, and social equity. UDTs can support this shift by enabling real-time monitoring, dynamic analysis, and feedback loops to inform adaptive urban decisions, provided that system-level management strategies are clearly defined and effectively operationalized.

In parallel, a distinct set of challenges arises from unequal data and technological landscapes across cities. Many low-income countries, already underperforming in achieving SDG targets, face persistent issues like data scarcity, poor data quality, and limited infrastructure (McCarthy, 2022). These constraints

hinder the effective development and application of UDTs, especially when compared to high-income countries like Switzerland, Finland, Australia, and Singapore. Without targeted support, these disparities risk deepening the digital divide and excluding already marginalized urban populations from benefiting from digital innovation. UDTs should accurately reflect the living conditions and needs of vulnerable communities such as those in informal settlements and slums (SDG 11.1), where data is often lacking. While data privacy concerns may also limit the willingness of some groups to fully participate, involving representative citizen groups in the UDT development process and the use of UDT-based participation tools is necessary to prevent marginalization and privatization.

Additionally, technical barriers such as interoperability issues and inconsistent data quality, highlight the need for research into common standards and protocols for data collection, integration, and sharing. To avoid excluding data-poor areas such as slums and informal settlements, it is important to prioritize reliable open data sources, and explore new data streams like VGI, social media, street view data, and satellite images. For countries with limited infrastructure, international collaboration and investment in data collection and analytics are essential.

To fully leverage UDTs for sustainable urban development, cities must adopt integrated strategies that address both technical and social dimensions of implementation. Efforts such as establishing open data platforms, fostering public-private partnerships, and enhancing digital literacy through capacity-building initiatives, as well as integrating replicable social and technical frameworks into policies and regulatory frameworks can significantly improve UDT adoption and effectiveness. Equally important is the development of replicable social and technical frameworks that can be adapted across diverse urban contexts, enabling knowledge transfer and reducing the learning curve. For instance, the FIWARE open-source platform (FIWARE Foundation, 2025), adopted by several smart cities in Europe and Latin America, demonstrates how shared frameworks can support cities of varying sizes and capacities in implementing interoperable digital services tailored to local needs. By pursuing these steps, cities can move toward a more equitable digital transformation, positioning UDTs as a key enabler of resilient, inclusive, and sustainable urban futures. Overall, the integration of UDTs into governance systems is not seamless and should be addressed carefully, especially by assessing existing UDT applications and validating the proposed framework in this study.

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