RESEARCH IN PROGRESS

Using Digital Twin Technology for Developing a Healthy and Sustainable Living Environment: A Dutch Case Study

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As urban environments face increasing challenges related to sustainability in development and planning, Digital Twin (DT) technology has emerged as a potential solution for enriching real-time and historical data into spatial planning processes. This study examines the potential and application of a DT in facilitating sustainable urban development, using the Utrecht Science Park (USP) as a case study to illustrate these possibilities. Specifically, the Healthy Heidelberglaan project, a collaborative initiative with different partners within the USP, demonstrates how this technology could support sustainable urban transformation. This research employs a methodological approach that includes sensor-based data acquisition, integration with external datasets and the implementation of scalable processes for historical data analysis. As this research is ongoing, subsequent phases will focus on development, translation of geographic data, analysing potential barriers and identifying key challenges and opportunities associated with DT technology and its application.

Keywords:
digital twin,
urban development,
internet of things,
sustainability,
GIS

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1 Introduction

The rapid expansion of cities and the increasing complexity of urban environments have heightened the urgency of addressing environmental challenges. Innovative solutions are required to monitor and analyze the impacts of urbanization, and to develop strategies that enhance environmental sustainability and resilience. Urban areas, being significant contributors to environmental degradation, have the potential to implement changes that positively impact the environment and public health (Vardoulakis et al., 2016). Integrating green infrastructure, improving energy efficiency, and promoting sustainable transportation are examples of urban changes that can mitigate environmental challenges (Mazzetto, 2024).

A Digital Twin (DT) is a virtual representation of a physical object or process capable of collecting information from the real environment to represent, validate, and simulate the physical twin's present and future behavior (Botín-Sanabria et al., 2022). In the context of spatial planning, DT technology has emerged as potential tool that facilitates data-driven decision-making and supports spatial planning (El-Agamy et al., 2024). By creating a virtual representation of physical spaces, DTs enable (continuous) synchronization for an accurate representation of the physical landscape, offering decision-makers dynamic and context-specific insights for informed decision-making (Mongo & Daidj, 2025).

DT technology is increasingly being adopted by local and regional governmental organizations in the Netherlands to support spatial planning decision-making and to balance contradicting policy ambitions (Nochta et al., 2021) . These DT solutions are becoming more complex as more perspectives, based on sophisticated calculations, are added to one integrated view of the problem space (Ranatunga et al., 2024). For example, integrating DT technologies with Geographic Information Systems (GIS) marks a transformative shift in geospatial analysis, enabling real-time monitoring and simulation of urban environments (Botín-Sanabria et al., 2022). This combination enhances the capability to analyze and visualize spatial data, which is an important capability for urban planning and environmental monitoring (Azadi et al., 2025; Botín-Sanabria et al., 2022).

Despite the potential of DT technology, there are still too few studies that approach this topic with case studies and empirical research, combining both the technical perspective and the challenges related, in the context of urban digital twins in the Netherlands (Mongo & Daidj, 2025; Oakes et al., 2024). Furthermore, our case is unique in a sense that it involves a large Dutch Science Park that serves a complex combination of zoning types in one shared area, i.e., living, working, traveling (e.g. by several options for transport in the form of bus, tram, bicycle, walking), recreation and study. To address this gap, we present a technical and empirical case study focused on the Utrecht Science Park (USP) in the Netherlands. The research question guiding this study is: *How can Digital Twin (DT) technology be utilized to support healthy and sustainable urban development, specifically in the context of the Utrecht Science Park (USP), and what are the key challenges and opportunities associated with its implementation?*

This paper is structured as follows: The next section provides an overview of the background and related work. Following this, we present the proposed research method and preliminary results of the case study. Finally, we discuss future avenues for research.

2 Background and related work

We identified two scientific contributions that have explored the application of digital twins in the context of sustainability and healthy living in relation to a science park. No relevant studies were identified that focus specifically on a Dutch case study. Fernandez et al. (2023) present the Smart DCU Digital Twin initiative, part of a broader Smart Dublin project aimed at developing intelligent, responsive, and adaptive urban environments through real-time monitoring and multi-stakeholder collaboration. It primarily addresses DTs as innovative tools for efficient infrastructure management, decision-making, and environmental monitoring in urban environments. The research integrates advanced 3D modeling, drone surveys (DJI Mavic 2 Pro), and Bentley's ecosystem (Context Capture, OpenCities Planner, iTwin Platform, Unreal Engine). IoT sensors used include occupancy, temperature, noise, illumination, and radar-based footfall counting sensors (WIA, CIVIC, HiData, Bigbelly). Bentley's 4D Analytics platform integrates and visualizes data, enabling predictive analytics. Challenges addressed include data management, interoperability, scalability, and stakeholder collaboration. This DT initiative effectively captures and analyzes campus environmental conditions and infrastructure usage, offering immersive and intuitive interfaces for stakeholders through advanced visualization technologies. The methodology demonstrates significant potential for applying DTs to multifunctional urban areas like science parks, effectively corresponding with your research question on DT technology utilization and its associated challenges and opportunities in sustainable urban development.

The paper by Lu et al. (2020) addresses the development of a digital twin (DT) at the building and city levels, specifically applied to the West Cambridge Campus. The primary research goal was to create a systematic and comprehensive DT framework supporting operation and maintenance (O&M), decision-making, and asset management processes. The developed architecture includes a multitier system comprising data acquisition, transmission, digital modeling, data/model integration, and a service layer. Technologies and data involved in the study included BIM (Building Information Modeling), Geographic Information Systems (GIS), IoT sensor networks, QR code-based asset management, and real-time sensor data. The IoT-enabled Wireless Sensor Networks (WSNs) were deployed to monitor environmental and equipment conditions, such as indoor temperature, humidity, HVAC system status, vibration, and other asset-specific data. The integration layer utilized MySQL databases to incorporate data from building management systems (BMS), asset management systems (AMS), and space management systems (SMS), along with UAV-based photogrammetry and laser-scanned point cloud data for spatial information. This comprehensive DT framework successfully supported O&M activities by providing real-time monitoring, predictive analytics, visualization capabilities, and enhanced human interaction, all critical for sustainable urban and campus development.

This paper frames Digital Twin technology not just as a technical solution but as a sociotechnical system as stated by Nochta et al., (2021). In this framework, DTs support decision making processes that are influenced by social values, policy structures and stakeholder interactions. This aligns the ambition to foster sustainable urban development by integrating technological infrastructure with the focus on liveability.

3 Research method & Preliminary Results

This research adopts a Design Science Research (DSR) (Hevner et al., 2004) approach, supported by a narrative literature review (Paré et al., 2015). The narrative literature review provides a broad summary and synthesis of existing research on a specific topic, focusing on key concepts, theories, and findings. It is flexible in structure, allowing for the identification of trends and gaps in the literature, and is particularly useful for exploring new topics or providing background context for research.

Following DSR, an artifact (DT-prototype) is developed, assessed, and refined to support development of the digital twin for USP. The prototype is designed to address a practical business need, i.e., assisting with data-driven decision-making that supports spatial planning by visualizing spatial data in one integrated 2D/3D environment., The development of the prototype is informed by applicable technologies, frameworks and methods identified in the literature presented in the previous sections. In this section, we further present our preliminary findings based of the first prototype version that makes up the first design cycle. The activities within this study are aligned with the stages of the DSR framework. First, in the identification stage, we identified the lack of data-driven decision-making for sustainable development of the USP. In the objectives stage, together with stakeholders, we defined the objective to focus on the development of a digital twin for the visualisation of spatial data from the USP. This was done based on two focusgroups and multiple qualitative interviews with different stakeholders focusing on requirements. Based on the output of the previous stage, we designed and demonstrated the DT prototype that visualizes static and dynamic environmental data collected from the USP. The DT prototype has then been evaluated with multiple stakeholders in the evaluation stage, leading to several improvements to be designed in the next iteration of the prototype. We disseminated the DT prototype and our findings both towards stakeholders using different mechanisms such as events and presentations as well as publishing a first paper (this work).

4 Data acquisition and sensor integration

The prototype leverages real-time environmental data collected via an IoT sensor network deployed across two main streets within the USP. These sensors measure a range of environmental parameters.

The collected data is transmitted to the SamenMeten API, managed by the RIVM (Dutch national institute for Public Health and the Environment). This API provides access to dynamic environmental data, collected in an hourly interval. An example snapshot of the dynamic data is presented in Table 1. Furthermore, we also collected static data for analysis and visualization in the digital twin. In total, we integrated seven GIS map layers, being sound, rainfall, tropical days, heatmap tropical days, shadowmap buildings and shadowmap bicycle and walking lanes. These were collected using public data sets with the help of the municipality and province of Utrecht.

Table 1: Example of Collected Data

ID	Name	NO2 (µg/m³)	PM2.5 (µg/m³)	Calibrated PM2.5 (µg/m³)	Temperature (°C)	Humidity (%)	Pressure (hPa)	Longitude	Latitude
1	SSK_USP02	2.45	2.5	2.28	18.77	56.47	1018	5.169	52.085
3	SSK_USP01	8.63	19.02	13.33	20.15	85.9	1019	5.164	52.084
4	SSK_USP03	17.8	20.3	25.74	-1.3	67.68	1017.63	5.172	52.085
5	SSK_USP04	15.57	17.93	13.93	6.33	73.05	1027.67	5.172	52.085
6	SSK_USP05	11.35	13.24	10.93	7.33	75.05	1028.67	5.172	52.085
7	SSK_USP06	9.35	11.24	9.93	8.33	76.05	1029.67	5.172	52.085

5 Data visualisation

To facilitate effective data interpretation, collected environmental data is visualized within a Digital Twin framework using ESRI ArcGIS software. The GIS-Based approach enables spatial analysis of the USP. This allows stakeholders to identify high risk zones and design targeted interventions. An example of two combined datasets is the general shadowmap and the shadowmap with bicycle and walking lanes in the area, presented in Figure 1. The grey areas represent shadow coverage from trees or buildings, while the cyan lanes represent walking and bicycle lanes. The digital twin quite effectively presents the spots that are not covered by shade. This information, for example, is relevant to combine with the heatindex-datasets, but this is omitted due to space constraints.

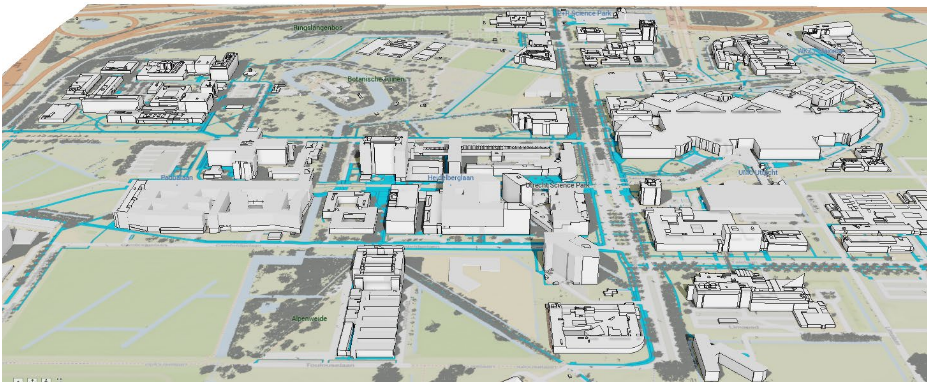

Figure 1: Example data visualization of shadow coverage and bicycle and walking lanes in ArcGIS (several areas are visible that show no shade at all for large areas)

To improve the development, we will first test it with all stakeholders. These include area development advisors, researchers, GIS experts, and software developers. These sessions will, for example, focus on decision-making utility and the relevance of the data.

6 Future work and research agenda

Future work will focus on several key areas to improve the artifact. A scalable database infrastructure still needs to be implemented to store and analyse historical environmental data from the IoT-network. Allowing different stakeholders to track environmental impact over time. See Figure 2 for the proposed database architecture for the next iteration of the artifact.

The data architecture is designed to facilitate integration with various external tools to improve the quality of the digital twin facilitated in the ESRI ArcGIS software. The system also needs to incorporate automated data validation processes to ensure safety, accuracy and consistency in historical records. Allowing different stakeholders to track environmental impact over time. Enhancing the Microsoft Azure Database structure to efficiently manage and store large volumes of historical data beyond the initial 200 entries currently supported by the SamenMeten-API is also to be added to the prototype in a future iteration.

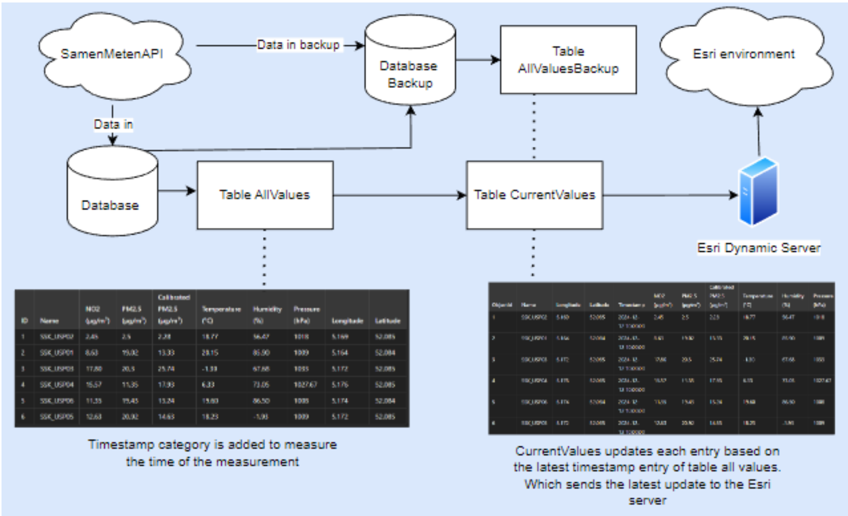

Figure 2: Dataflow process of Historical data

The prototype can be further enhanced by the development of additional GIS layers to visualize complex datasets, such as underground infrastructure and living experience surveys, enhancing stakeholder understanding of subsurface networks and user experiences. Continuous expansion of real-time data visualization capabilities, integrating various external and internal datasets, thus providing comprehensive insights into the multiple factors influencing Utrecht Science Park. Research and implementation of Geospatial data within the Digital Twin, translating complex sensor and GIS data into visualizations.

Extensive deployment of sensors across the entire Utrecht Science Park presents logistical and practical challenges that cannot be addressed within a short timeframe. Moreover, as areas within the park undergo redevelopment, existing sensors may need relocation to ensure continuous and accurate data collection. Therefore, future research should prioritize developing robust methodologies for extrapolating sensor data beyond their immediate measurement range. To support these extrapolations, nearby sensors could serve as validation points to ensure accuracy and reliability. However, this approach has limitations, particularly concerning parameters influenced by highly localized microclimatic conditions, such as soil moisture. Also, the current density of sensors is very low and we will focus on expanding the sensor network to improve validity of the data in a next iteration.

Furthermore, a future iteration should include an accessible public web portal that transparently displays non-sensitive information including real-time sensor data visualizations, historical trends, and interactive maps. Also, the prototype should include a secure, researcher-exclusive portal with advanced analytical tools, data export capabilities, and customizable visualization options for in-depth scientific exploration and analysis.

Lastly, it is important to gather insights from all stakeholders regarding the challenges experienced. Further empirical research is necessary because the prototype is not merely a technical implementation; it is a socio-technical solution and must therefore be investigated as such. To further develop the prototype, the values of stakeholders should be further identified and tested using future iterations. This is fundamental for the successful sustainable usage of digital twins as a technology for spatial planning in the context of the USP.

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