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Humans As Sensors in Urban Digital Twins

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Abstract. Digital twins have gained increasing attention as a tool to facilitate decision-making in the cities. However, the current discourse predominantly focuses on technical aspects while overlooking the human aspect in urban digital twins. This work proposes a conceptual framework that addresses the role of humans in relation to the urban environment, therefore highlighting the social value of urban digital twins. The proposed framework is subsequently implemented in a specific case study of outdoor walking comfort at National University of Singapore, validating its feasibility in practice. By incorporating human sensing data, such as participatory data, urban digital twins have the potential to represent the dynamic interaction between people and environments, generating a holistic physical-social-virtual system.

Keywords: Urban planning, Participatory process, Human sensing data, Data integration, 3D city modelling

1 Introduction

Urban digital twins facilitate planning and construction in cities, as the means of modelling physical assets and implementing dynamic scenarios. By integrating data from various sources and utilising technical tools, digital twins enable an interactive loop between virtual and physical environments, thereby supporting efficient decision-making and cost-saving measures [1, 2, 3]. While the potential is well identified in the community, the social aspect is often overlooked in the whole lifecycle of urban digital twins. However, a shift towards a socio-technical perspective has been recently noticed in the current discourse surrounding urban digital twins, with increasing attention being paid to social and legal considerations [4, 5]. We posit that urban digital twins, as the interdisciplinary concept, should provide insights into city planning and decision making, beyond the demonstration of technical functionality. However, there remains a research gap in developing a framework that considers the social aspect in urban digital twins and dynamically incorporates such information. As such, we identify two main aspects related to social and human value, addressing the socio-technical trend and enhancing the development of urban digital twins. First, since urban digital twins are built in various initiatives and regions, the accessibility of these models are scattered and unequally distributed around the world. It is implied that some digital twins are enclosed without public access, leading to a concern of lack of openness. Non-public models have insufficient evidence to demonstrate their purposes and capabilities to facilitate city management. In other words, an absence of public participation ignores the role of people in cities, resulting in an unclear position of digital twins in the urban realm. Second, collaboration among a variety of stakeholders (e.g. government, companies, research institutes and organisations) is an emerging topic in the field of urban digital twins, associated with, for example, data sharing and policy making in the local contexts. In relation to the first point, the human part is a significant component in urban digital twins, including but not limited to open accessibility and multistakeholder engagement. In this context, an inclusion of human aspect should be considered to enhance social value in urban digital twins, as well as improve the current socio-technical trend.

With the emergence of social networking, the role of human participation can be described as data sources from sensing information via explicit recruitment or implicitly by contributing on platforms [6]. Human sensing data presents an input source relying on collecting data by humans or by sensors acting on their behalf. Such human-centric sensing has been studied in strands of fields, from psychology to sociology, as a means to collect sensing data and gain insights into human behaviours [7, 8, 9]. Following the societal trend in the research communities, urban studies have increasingly embraced this concept to investigate the interaction between people and cities, e.g. leveraging human sensing data to understand urban changes [10, 11]. As a new tool of the digital revolution in urban domains, digital twins have a strong demand for dynamic information (e.g. data collected from IoT infrastructure) to manage cities in the real world [12, 13]. While such sensors can support the twinning of the built environment in digital twins (e.g. gathering real-time weather data), they fail to capture the crucial aspect of the interaction between people and physical surroundings. An urban digital twin integrates the input of human sensing data (e.g. participatory and collaborative information), demonstrating the potential to reflect social activities and provide solutions for the uncertainties and complexities of urbanism [14, 15]. In this sense, such a digital twin model indicates the capability to simulate urban scenarios, collect feedback from people, and facilitate human-environment interactions, eventually generating a dynamic loop between the physical, social, and virtual environments within the system. For example, a human-centred urban digital twin can be employed to examine political decisions regarding infrastructure, as an approach to enhancing resilience among people and communities, by integrating multiple sensing data from local citizens [16].

This work raises two research questions: (1) How to incorporate the human aspect in urban digital twins? (2) What value can the concept of humans as sensors add to urban digital twins? These questions highlight the importance of considering the social and human dimensions in urban digital twins and exploring the potential benefits of using human sensors to gather valuable data for digital twin models. A conceptual framework is developed to integrate human sensing data (e.g. through a participatory process) in the lifecycle. Subsequently, the proposed framework is implemented in a specific area at National University of Singapore. In the case study, 15 participants recruited to collect sensing data, function as sensors, when performing outdoor walks, by wearing digital devises. Four data sources are gathered, which are comfort feedback, noise data, solar intensity and the percentage of urban objects in the surroundings. This case study aims to investigate how people interact with the built environment during walking, by analysing human sensing data. Meanwhile, it is proved as an example of validating the feasibility of our conceptual framework, namely examine the interaction between people and the surroundings with the aid of urban digital twins.

2 Related work

For years, human sensing data, described as a collection of digital information generated by individuals to disseminate their feelings or experience on social platforms, have received wide attention in numerous studies [17, 18, 19, 20, 21]. Large-volume human sensing data can convey a wealth of information based on human activities at various scales. Regardless of personal background and knowledge, such data offers valuable insights into how people interact with their environment and engage in different activities. In some cases, geospatial information embedded there, such as check-in data from platforms like Yelp and Tripadvisor, and geotagged images from services like Flickr, can be useful in understanding local contexts [22]. Through extracting spatial and temporal information, these human sensing data can support a wide range of research objectives, for example, disaster management, problem reporting, social behaviour and urban dynamics [23, 24, 11]. For example, one of the most prominent applications is concluding man-land relationship by interpreting multiple human sensing data to recognise urban functions and land cover [25]. Furthermore, Tu et al [26] conducted research on portraying urban vibrancy of Shenzhen by analysing three types of crowdsourcing data. Ballatore and De Sabbata [27] investigated place representation by comparing four crowdsourced content datasets and their context, forming a holistic understanding of urban life. Moreover, human generated data is also popular in characterising demographics (e.g. income, job-housing relationship) and then further inferring urban development [28, 27]. Through extracting socio-economic features from such data, urban sprawl and urban deprivation are discussed in the scholar studies, revealing the city as a social system intertwined with human activities [29, 30]. As such, this large-size amount of human sensing data has gained popularity as a supplementary source to demonstrate human activities. associated with demographic, socio-economic and environmental factors [31, 26].

Cities are an integrated system of elements, including human, assets, environment and their interaction, which are more complex than others [32]. Emerging discussions expose an interest in socio-technical issues to address digital twins' functions beyond technical aspects. Batty [33] identified one request in digital twins as merging socio-economic process into the built environment. A proposed method is to involve humans as sensors through their smartphones and integrate with physical information (e.g. traffic, building, energy), shaping a comprehensive data network. In the case of including people in urban digital twins, sensing data enable a glimpse of the nature of cities, e.g. how the city works, how human activities represent the city, and how their socio-economic characteristics affect the city. Applying urban digital twins to achieve such idealisation fully is illusory at present, however, some efforts have been carried out in the current research landscape by exploring mechanisms to include people in digital twins as a primary step. Dembski et al [34] presented an urban digital twin of Herrenberg as a means to engage people in the planning process. Such participation is conducted with virtual reality (VR) in the digital twins, supported by various dialogues between councillors, experts and citizen. People can share feedback and visions of future planning based on local knowledge. Urban digital twins support such participatory processes in a virtual environment and are easily accessible to different groups regardless of their backgrounds. Similarly, White et al [35] delivered a participatory digital twin for Dublin. The study applies the model to simulate flooding scenarios, aiming to design corresponding strategies for the city. Given the cited work's motivation, local citizens are invited to the planning process, providing feedback and detecting errors in such simulations. Considering the growing interest in citizen engagement, Abdeen and Sepasgozar [36] proposed a framework with different layers to facilitate community participation in the urban digital twins. Besides involving public participation in different ways, another strand of research addresses socio-economic values by modelling human activities in urban digital twins. Klebanov et al [37] approached a method to digitalise humans as agents and simulate their dynamics depending on individual needs, intending to effectively implement strategic planning. Such a means enhances the position of people in the planning process and, at the same time, unfolds the potential to represent physical infrastructure and behaviour patterns in the digital twins. This consideration has also been adopted in simulating disaster scenarios. Fan et al [38] proposed a framework to evaluate infrastructure disruptions based on analysing social sensing data in the enhanced digital twins.

Overall, a socio-technical trend has been emerging in the current discourse surrounding urban digital twins, addressing the consideration of humans. Motivated by the utilisation of human sensing data in other related fields, we intend to propose a conceptual framework that incorporates social and human dimensions into urban digital twins. To the best of our knowledge, this framework represents a novel approach by including non-technical values in urban digital twins and leveraging human sensing data to represent social activities within such models.

3 Conceptual framework

The methodology is designed with two parts: data deployment and system management (Figure 1). First, human-centred urban digital twins are built upon multiple data sources, such as from crowdsourcing, social sensing and partic-

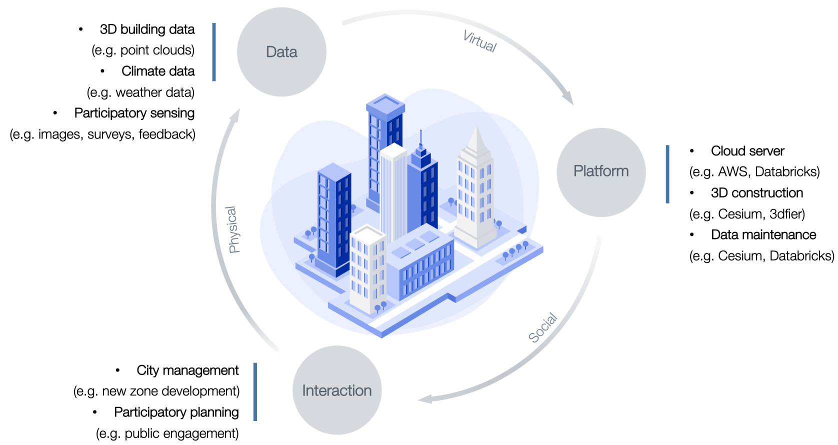


Fig. 1. The framework of human-centric urban digital twins.

ipatory sensing, considering the features of people in social, cultural, and environmental dimensions. Taking participatory data as an instance, these data are directly contributed by participants that recruited for specific urban studies, such as information from wearable devices [39], responses to questionnaires [40], and feedback provided while interacting with urban digital twins [35]. By integrating such information into urban digital twins, they can represent individual perceptions of urban environment and simultaneously promote the role of people in the decision-making process. In this sense, deploying multiple types of data that indicate people factors has the potential to mirror how people perceive and behave in the virtual environment. With the consideration of such social and human aspects, digital twins facilitate the interaction between people and the urban environment while adding social value to their lifecycle.

The second part focuses on system management, including 3D construction, data update and maintenance. The core aspect involves automatically mapping dynamic data into a digital twin platform. We design our platform by utilising a browser-server architecture, ensuring maximum compatibility and interoperability with future input data and software. Our method incorporates the use of Cesium, an open-source platform, which supports data integration and online visualisation. The construction of 3D building models is achieved by extruding building footprints according to the height information, as well as enriching with semantic information, such as building types, the construction of year, roof types, building materials. Data collected from human is linked with geospatial location and then integrated into our platform in multiple formats, such as 3D Tiles and GeoJSON. Such mainstream data are represented using Cesium Markup Language (CZML), enabling real-time geospatial information exchange within the Cesium virtual earth [41]. For instance, Cesium allows us to integrate mobility data that contains trajectory-related information, e.g. heart rate and walking speed. This information can then be integrated with urban phenomena such as urban shading, serving mobility analysis in the digital twins, e.g. pushing real-time notifications to pedestrians to suggest a comfortable and walkable route. Overall, the interactive simulations have the potential to identify possible consequences of proposed urban strategies and facilitate decision making.

4 Case study

4.1 Study area

The conceptual framework is proposed to enhance the social value in digital twins at different urban scales. As an urban digital twin should represent the city ecosystem, various human activities and multi-functional buildings and spaces need to be included when implementing such a framework. That is, the features and coverage of the study area need to be reasonable to indicate the urban context. In this sense, this framework is applied to the Kent Ridge Campus at National University of Singapore (Figure 2). The study area encompasses more than 300 buildings, covering a variety of uses, such as educational buildings, recreational facilities, and infrastructure. Such diversity can be considered to represent the campus as a suitable case study for a digital twin at the district or urban scale.

4.2 Data collection

This case study includes two primary data sources: publicly available data and participatory data. Publicly available data, such as OpenStreetMap data, is used to generate 3D representations of buildings on the campus, including building footprints and essential semantic information such as name, types, height, and number of floors [42]. Regarding participatory information, 15 participants (NUS students) were recruited to wear digital devices and collect data related to walking comfort and environmental factors. In detail, Cozie [4], an open-source iOS application built on the Apple Watch, was deployed to collect heart rates and comfort feedback when walking on the selected trajectory. Panoramic street view images were collected using GoPro cameras to represent the built environment at each location where participants submitted their comfort feedback. Noise data was recorded by the sound meter and solar intensity was monitored through Photometer application[5] on a smartphone. The experiments were performed thrice daily, with a single participant per walk, commencing at 10 am, 2 pm, and 5 pm, attempting to include multiple outdoor conditions. As such, participants function as sensors, collecting comfort perception data along with, e.g. location,

[4] https://cozie-apple.app/
[5] https://photometer.pro/

Fig. 2. Study area: Kent Ridge Campus, National University of Singapore. Sources: (c) OpenStreetMap contributors and Google Street View.

timestamp and factors related to the built environment. A statistical plot summarises different values collected through the experiment in Figure 3. Such data were subsequently integrated into the digital twin campus for showcases and analysis.

4.3 Data integration

Integration is identified as a key challenge of urban digital twins [5], involving system compatibility, format conversion, and other factors. In this case study, Cesium is designed as the platform and two types of data sources are included. Considering that the platform is browser-based and uses HTTP for visiting, all integrated data should be in a JSON-based format as input for Cesium. First, building data is downloaded from OpenStreetMap as an .osm file, and extracted through QGIS. FME (Feature Manipulation Engine), a robust tool for integrating and transforming spatial data, is applied to create 3D tilesets in JSON format, for extruding building footprints. Second, for the panoramic photos, they are segmented using DeepLabv3 [43], to derive the percentage of urban objects visible from a viewpoint along the route. Four classes, namely *sky*, *building*, *vegetation* and *terrain*, are selected to represent the physical environment in this work. All participatory data is stored in a CSV format (15 CSV tables for 15 participants), and converted into JSON file in Python using Pandas library. A

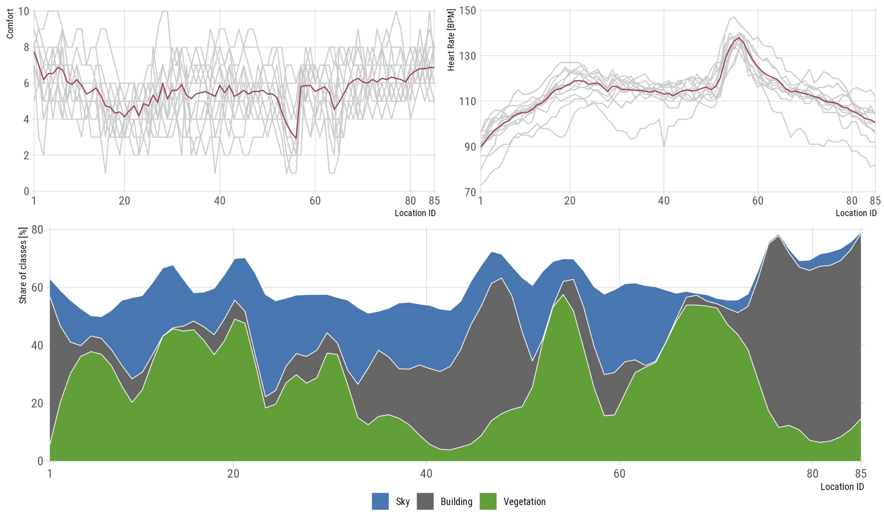
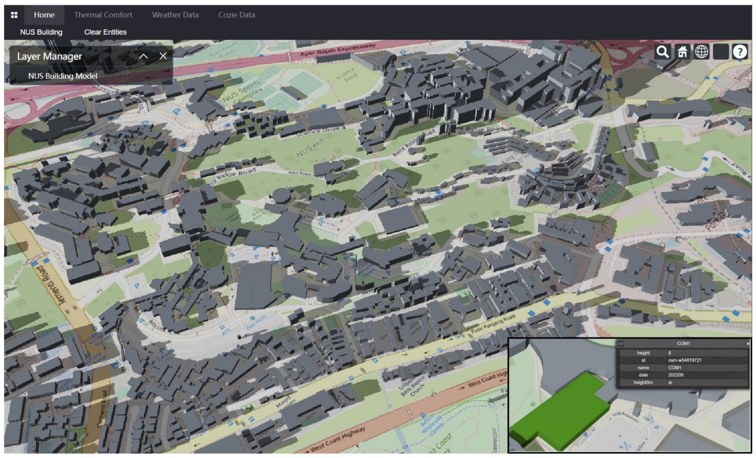


Fig. 3. Collecting participatory data from human sensing. The top plots show participants' biometric values during walking along the selected path. The bottom plot demonstrates the built environment. Data courtesy of Liu et al [40].

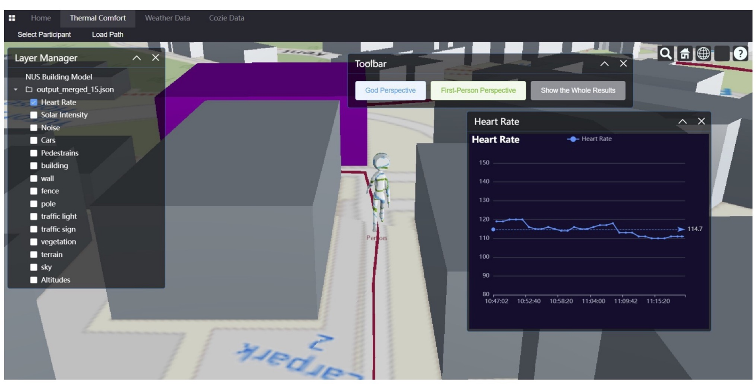
REST API is built to access and retrieve data via HTTP requests, which can be simultaneously parsed into the Cesium platform for further visualisation and analysis.

4.4 Implementation

3D buildings are generated from OpenStreetMap data according to heights or the number of floors. OpenStreetMap data in Singapore is of excellent quality [44], and thus, suitable for this research. Most buildings have semantic attributes such as name, height, levels, and type, while a small portion of them have additional roof-related information, such as roof type and roof colour. The 3D Tiles of buildings are visualised on Cesium, representing a simplified virtual model of campus. Participatory data is converted into CZML format as an input for online visualisation. Each walk performed by participants includes 85 locations around the College of Design and Engineering (CDE) of the National University of Singapore. The path in focus has a distance of approximately 1.7 km and includes a mixture of physical conditions, such as outdoor sidewalks, open spaces, and semi-open spaces (e.g. sheltered areas between two buildings), and heterogeneous scenes (e.g. varying greneery visible). Since the data is collected as location points, a walking trajectory denotes the connection of each point enriched with time-series data. A 3D human model is prepared to represent individual participant and simulate outdoor walks on the platform. When the human model moves along the trajectory, a figure displays dynamic changes in sensing data under different categories, e.g. heart rate and solar intensity (see Figure 4).



(a)



(b)

Fig. 4. The implementation of the conceptual framework at NUS campus. The top plot (a) presents 3D buildings in Kent Ridge Campus, National University of Singapore. The bottom one (b) demonstrates the dynamic interaction between outdoor walking and the surroundings. Source: (c) OpenStreetMap contributors.

5 Discussion

The concept of humans as sensors provides insight into representing social activities in urban digital twins. The lens of human sensing pushes forward the socio-technical shift in the current discourse, taking into account the social and human aspects. In this sense, the conceptual framework proposes the characteristics of social and human aspects in urban digital twins. Two features (i.e. openness and availability) are considered in the framework, regarding the encouragement of using publicly available data and open-source tools. In terms of added value from the social dimension, we deem that human plays a role in cities, offering opportunities for crowdsourcing and sensing information. As such, the concept of humans as sensors is applied in the conceptual framework, aiming to integrate sensing data and enhance the dynamic interaction between people and the environment. Validating the capability of the proposed conceptual framework, we further implement it on a campus area at National University of Singapore. The generation of such a digital twin model relies on public data and open tools, which is based on an online browser, enabling a user-friendly interface. Meanwhile, through designing a participatory process, sensing data collected by participants is integrated into the platform, demonstrating the interaction between individual perception and the built environment. With the aid of deploying public data and utilising open-source tools, a human-centred digital twin offers increasing possibilities to encourage public participation and openness among different groups of stakeholders. The dynamic interaction enables dynamic data representation in urban digital twins and provides timely feedback based on the simulation of various scenarios. The proposed framework of human-centred digital twins takes into account significant characteristics of urban digital twins, such as dynamic information exchange and the human aspect. In the presented adoption in the campus of National University of Singapore, we incorporate thermal comfort and physiological data collected from participants into our digital twin model, along with public data (e.g. 3D buildings and climate data) with a representation of the physical environment. Through this proof-of-concept, we demonstrate the potential of integrating participatory sensing data to visualise and simulate the dynamic relationship between people and urban environments.

In terms of use cases, this proposed framework presents the scalability to serve multiple purposes in the urban realm. For example, the results of previous case study can be scaled to the entire campus. By extracting environmental factors from street-level images (e.g. volume of visible vegetation), a potential use case can be using information from the built environment to infer human comfort during walk. With the predicted comfort data, a relationship between environmental factors and individual perception can be examined in a large scale, which subsequently supports further studies. For instance, by integrating such information in the digital twin prototype, we can assess the greenery in the campus and simulate multiple walkable paths for pedestrians. A limitation should be elaborated in future studies is regarding data-related issues. First, considering participatory information, data privacy raises concern which hinders a large-scale deployment in urban digital twins. The access to such data is limited, as well as the recruitment and participation can be time-consuming and subject to cases. Moreover, the reliability is acknowledged as a key issue in urban digital twins when utilising such information for use cases. Besides data collection from participatory process, other types of human sensing data can also be considered as a representation of social activities in the proposed framework. Taking crowdsourced data as an example, OpenStreetMap data used for generating 3D buildings is contributed by volunteers who manually map or edit features, inevitable entailing data noise or accuracy-related barriers. In future research, we aim to explore possible use cases by adopting this conceptual framework, illustrating the inclusion of human and social values beyond data collection and visualisation. Furthermore, a detailed discussion of data privacy and reliability will be conducted as part of our long-term motivation, addressing the lifecycle of urban digital twins.

6 Conclusion

This work develops a conceptual framework of urban digital twins, considering social and human elements which are largely overlooked in the current discussions. Regarding the comprehensive architecture, this framework encourages openness and availability of urban digital twins, and subsequently involves multiple groups of stakeholders in the development process (e.g. government, companies and research institutes). In this context, data integration includes a variety of publicly available data, such as 3D buildings, crowdsourced information and environmental factors. Open-source tools are also recommended for 3D reconstruction and visualisation, for example, Cesium platform. Meanwhile, regarding the nature of urban data, management and maintenance service are considered to update dynamic changes between the physical and virtual environment. That is, enabling interactive simulations on the system. Such architecture of the proposed framework acknowledges the lifecycle of urban digital twins from data collection to system management. Human sensing data as an input highlights social and human dimension in the framework, for example, representing human activities and reflecting the interaction between people and the built environment in urban digital twins. This conceptual framework is implemented on the Kent Ridge Campus at National University of Singapore. Leveraging participatory data to analyse how individuals are affected by the surroundings in the case study, our framework offers the feasibility for embedding social and human value in practice. We deem the proposed framework as an initial step to address socio-technical trend in urban digital twins, as a means of integrating multiple functionality beyond the technical aspect.

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