Contemporary development directions for urban digital twins

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Keywords: Urban digital twin, Smart city, Social digital twin.

Abstract

Urban digital twins have become an interest for cities worldwide. The current urban digital twins frequently build on earlier 3D city modelling efforts, and thus also share many of the applications. At the same time, the ongoing digitalization offers potential routes for further development of urban digital twins. We present some of the ongoing development projects from the Helsinki region. Based on these, we then try to identify the contemporary development directions for urban digital twins, with the three emerging main themes being: 1) the inclusion of new data sources such as satellite remote sensing, crowdsourcing and various sensor systems, 2) a stronger presence of social aspects and qualitative data and 3) modular technical architecture.

1. Introduction

Most authors pin the term "digital twin" to have originated from product lifecycle management in the early 2000's (Jones et al. 2020 & Kritzinger et al. 2018). While detailed definitions separate "digital models", "digital shadows" and "digital twins" (Kritzinger et al., 2018), the precise meaning of a digital twin remains quite open, especially outside the research literature.

Digital twins have also become an interest for cities, resulting in "urban digital twins", "city digital twins" or "digital twins of cities". While taxonomies exist (D'Hauwers et al., 2021), the terminology remains ambiguous.

Several cities have taken steps in developing their digital twins, including Zürich (Schrotter & Hürzeler, 2019), Vienna (Lehner & Dorffner, 2020), Helsinki (Hämäläinen, 2021). In practice, many of the urban digital twin efforts are heavily based on 3D city modelling: In the Digital geoTwin Vienna, the aim is to "*...use the existing three-dimensional surveying and mapping data and potentially further input data to directly model a Digital geoTwin—a virtual, semantic 3D replica of all elements and objects of the city.* " (Lehner & Dorffner, 2020). In the example from Zürich, "*The digital twin is a spatial, digital model of the City of Zurich for different themes. It extends the existing spatial data infrastructure with 3D spatial data and their models and describes it.* " (Schrotter & Hürzeler, 2019). In both cases, the digital twin is very much portrayed as the continuation of the 3D city model. Thus, we can assume that the immediate implementations and applications of urban digital twins are also very close to those earlier associated with 3D city modelling (Biljecki et al., 2015).

At the same time, ongoing digitalization potentially continues to offer avenues for development for urban digital twins as well. Thus, it is not yet self-evident what elements these urban digital twins may include and what their use cases are–beyond the already established 3D city models for urban planning.

In this work, we describe the ongoing development activities of urban digital twins in the context of Helsinki. Based on these, we aim to identify the emerging, central themes of development for the urban digital twins, and discuss their future.

2. Contemporary development of urban digital twins

In the following, we review some of the recent and ongoing development projects, focusing on their approach to the development of urban digital twins.

2.1 Satellite remote sensing

The concept of utilising satellite imagery for monitoring urban environments and changes in them is well-established in research literature. The potential of data integration between existing urban datasets and satellite imagery was already mentioned in the early 2000's (Miller & Small, 2003). A more recent development has been the introduction of machine learning algorithms to support the interpretation and integration of remote sensing data in urban contexts (Li et al., 2023).

Despite the advantages in research, satellite remote sensing still remains underused and its properties and benefits are largely unknown by urban professionals. This may be due to the lack of real-life proof-of-concepts, outside the research literature. Furthermore, some parts of space- and satellite-based services likely need to reach a more mature stage to be employable in urban settings.

Via a Pre-Commercial Procurement, the cities and regions in the Horizon Europe-funded SPACE4Cities project (https://space4cities.eu/) will work closely with companies to develop at least five different replicable solutions for better and more dynamic management of public areas, green spaces, transport infrastructure and city maintenance – and cities' overall resilience to unexpected events or weather phenomena.

Earth Observation services provided by the European Space Agency's Copernicus programme and the positioning services provided by the Galileo programme are to be utilised to dynamically manage public areas and infrastructure. These services will need to be combined with other data sources to come to innovative, efficient and cost-effective services that meet the cities' needs and could eventually be integrated with cities' digital twins.

The municipalities of Helsinki, Amsterdam, Guimaraes, Ghent and the region of Athens - completed with 10 Replicator Cities

https://doi.org/10.5194/isprs-archives-XLVIII-4-W10-2024-177-2024

via the Open and Agile Smart Cities network - have 2.8 million Euros for European companies to develop innovations to manage public areas using space data between 2025 and 2026. Through a phased approach, the companies need to demonstrate the technical and economic feasibility by piloting solutions and services that reach beyond the current state-of-the-art.

Horizon 2020 funded Spotted project (https://cef-spotted.eu/) is exploring the potential of high value datasets, such as open satellite data, in management and governance of green areas. The goal of the project is to produce new insights on suitability and usability of satellite data in urban context. From the Digital Twin perspective, the project unpacks the potential to integrate satellite imagery but also machine readable data from satellite images to existing urban information systems and furthermore to real maintenance and management processes of green areas in the pilot cities Helsinki, Milan and Naples. The explored topics and data produced include e.g. green indexes (e.g. NDVI), heat exposure and heat vulnerability. Figure 1 provides an example of NDVI in a Helsinki subdistrict and population pressure against green areas from Helsinki's public area registry.

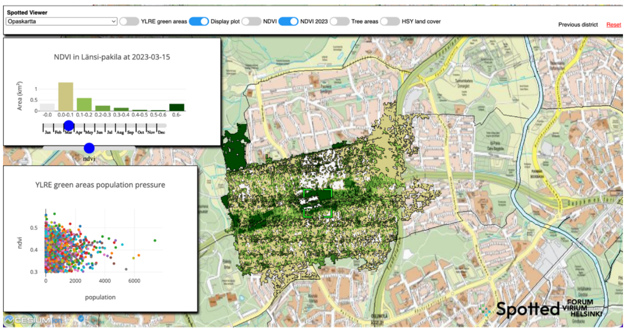

Figure 1. NDVI and green areas population pressure in Länsi-Pakila subdistrict. Data has been produced in the Spotted project utilising open data from the city of Helsinki and Sentinel Hub (https://www.sentinel-hub.com/). Data integrations and visualisations have been produced with the same tools that the city of Helsinki is using. Background map © OpenStreetMap (openstreetmap.org/copyright)

2.2 Digitalization of urban mobility

Mobility Lab Helsinki -project aims to support the development and testing of new innovations and enable new business opportunities in safe and sustainable mobility (https://mobilitylab.hel.fi/).

In addition to new mobility solutions, the digitalization of urban mobility is creating new data sources. One of these is "floating car data", referring to positions, timestamps and other telemetry harvested in a large scale from e.g. navigation apps or vehicle systems (for example, see Blumthaler et al., 2020). Lidar (Light Detection and Ranging) sensors are also increasingly tested for traffic and pedestrian counting (see e.g. Lesani et al., 2020). In this context, one of their advantages is the ability to monitor multiple traffic modalities with the same sensor. Additionally, 2D Lidar is often considered less of a privacy issue than e.g. camera installations. Combined, the new data sources provide a significantly more detailed "picture" of urban mobility than what can be attained with traditional traffic counting methods, such as stationary detectors. This creates a potential for traffic simulation and management. The project ACUMEN (https://acumen-project.eu/) aims to create new methods and tools for urban mobility management, leveraging some of these technologies.

Many of the autonomous systems currently piloted in cities worldwide also carry a significant amount of sensors to facilitate their own navigation in complex urban environments. As these also include sensors typically used in mobile mapping (i.e. combination of Lidar, IMU (Inertial Measurement Unit) and GNSS(Global Navigation Satellite System)) they also possess some potential for mapping urban environments, especially for roadside features (Hyyppä et al., 2023). Figure 2 provides an example of a point cloud originating from an autonomous logistics robot, piloted in Helsinki.

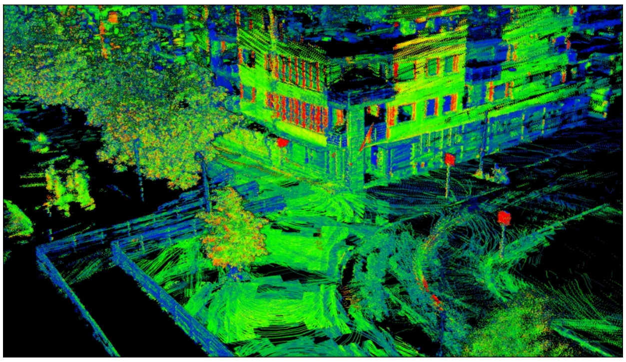

Figure 2. Example of a point cloud from a logistics robot. Original point cloud courtesy of GIM Robotics, from LMAD project (https://www.lmad.eu/).

Together, the new potential data sources related to urban mobility and the potential for also applying the new mobility systems to survey the urban environment is challenging the conventional, city-led surveying practice. Traditionally, the urban surveying operations have been specified and procured by the city organisations that have then also acted as data owners and distributors. With multiple providers, users and handlers of data, we are moving towards an ecosystem of urban mobility data. As many of the new data sources come from commercial providers, the concept of data marketplaces to facilitate these ecosystems has risen. The project SEDIMARK (https://sedimark.eu/) aims to design and prototype a networked data and services marketplace.

2.3 Digital twins for socially just climate adaptation

In the Regions4Climate project (https://regions4climate.eu/) the aim is to support climate change adaptation in socially just ways. While working with satellite-based surface temperature data, socio-economic perspectives help to better understand where climate risk overlaps with social vulnerability. This potentially allows for targeted adaptation policies that prioritise citizens facing the highest risks.

Vulnerability to climate change depends on risk and hazard but also a person's socio-economic position (e.g. age, health, and economic preparedness for climate hazards). To adhere to ethical principles regarding privacy when using socio-economic data, we developed a climate change vulnerability index that incorporates various socio-economic datasets, including age, income level, and education level.

The project aims to develop a "digital twin tool", an online 3D viewer application (Figure 3) that facilitates the study of different datasets related to urban climate risks (in particular, heat islands and urban floods) together with data on existing building stock and socioeconomic variables. While the final functionalities of the tool are yet to be defined, it is apparent that by providing a joint visualisation the tradeoffs and prioritisation issues associated with just climate change adaptation become much more apparent than with detached data sets. In addition, the viewer helps bring people working with climate topics together and foster discussion about climate change adaptation.

Figure 3. An urban scene with buildings coloured by their estimated heat stress. The diagrams compare the heat stress and amount of nearby vegetation of an individual building to the average of its postcode area. Land cover classification data shown from Helsinki Region Environmental Services HSY, Building footprint vectors shown from the City of Helsinki Urban Environment Division.

2.4 Age-friendly cities by crowdsourcing & data analysis

Participatory data collection was one of the key thematics of Horizon funded Urbanage project 2021-2024 (https://www.urbanage.eu/) that explored the potential of new technologies to build more age-friendly cities. In Helsinki, the focus was on inclusiveness and utilisation of existing datasets to produce valuable insights to support city decision-making and quick assessment of urban space.

One key outcome of the project in Helsinki was a design and production of a participatory data collection tool (Figure 4) for crowdsourcing citizen-generated data. This IoT (Internet of Things) device was co-designed together with city stakeholders and older citizens. The city of Helsinki already has several means to collect data and feedback from the citizens, and thus also data integrations and systems interoperability were explored further. From a user perspective, data collection methods may have limitations and issues with inclusiveness which can cause biases in data. For example, citizens have varying capabilities to use digital tools designed for participation and crowdsourcing.

The developed device was designed to ease participatory data collection in different engagement settings and support existing modes of participation. Collected data is fully anonymous and is available to developers and experts through open API (Application Programming Interface). As the data is saved in a commonly used standardised format (GeoJSON, Geospatial JavaScript Object Notation), it can easily be integrated with any existing tools and information systems that city stakeholders and potential city services providers are using in their normal operations.

Figure 4. Participatory data collection tool. The device was designed to be used outdoors, in urban spaces to collect simple, location based feedback data.

During the project, the device was utilised in Malmi district (Helsinki, Finland) to crowdsource information on desired locations for benches and additional street lights (Figure 5). The city of Helsinki organised data collection sessions with older residents from the area and the data was used to inform the city's decision making regarding new bench installations and quality of street lighting.

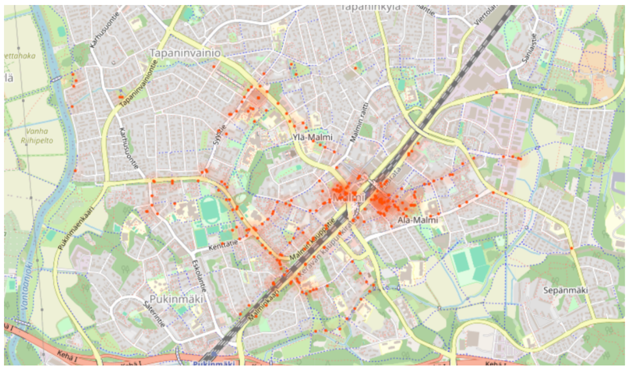

Figure 5. Data collected with the participatory data collection tool in Malmi district in January 2024. Background map © OpenStreetMap (openstreetmap.org/copyright)

As data formats and sources expand, DT (Digital Twin) requires new tools that can support planners and other civil servants to explore and categorise big data without specific technical skills. Interactive user interfaces (e.g. Figure 6) can ease assessment and help to narrow down the investigated phenomena. These can also assist dissemination of information that might be valuable for policy making and public participation.

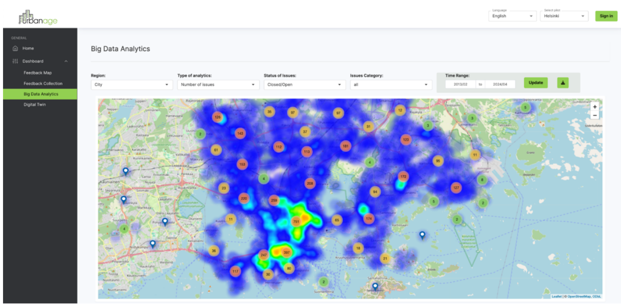

Figure 6. Citizen-generated feedback data visualised in an interactive user interface in Urbanage platform (https://ui.ecosystem-urbanage.eu/). Background map © OpenStreetMap (openstreetmap.org/copyright)

By combining the new data sources and existing geodata, new analyses can be developed. These aim to approach phenomena and properties of the urban environment that are difficult to survey with individual sensors. For example, in the Urbanage project, Flanders pilot developed a Green Comfort Index (see: https://www.urbanage.eu/flanders-use-case-1) to assess and identify comfortable public spaces. The perceived green comfort was estimated by forming a combination of urban GIS data and citizen-generated feedback (Figure 7).

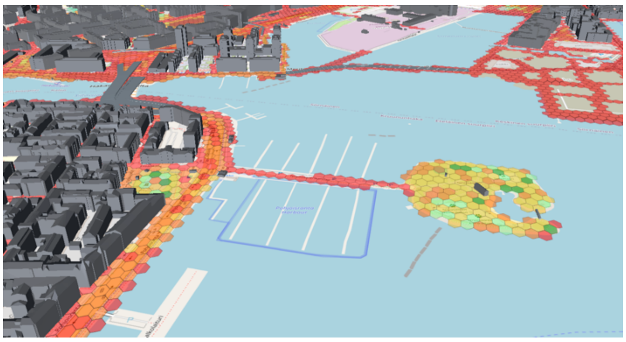

Figure 7. An example of green comfort calculation visualised in the Digital Twin user interface of the URBANAGE Platform (https://ui.ecosystem-urbanage.eu/). The calculation in Helsinki is based on open data on urban infrastructure and green areas. The 3D city model of Helsinki courtesy of Helsinki city executive office.

3. Discussion

To summarise, we can observe that there are several ongoing development directions for urban digital twins that we can identify. These include the introduction of new data sources and an increasing integration of social and socioeconomic aspects into urban digital twins. These also push towards a modular configuration of urban information systems. In the following, these are discussed in more detail.

3.1 New data sources for urban digital twins

Data sources applied for 3D city modelling are typically relatively similar across different cities, including airborne laser scanning, airborne photography, 2D GIS (Geo Information System) and various registers. In addition to such well-established geodata, additional, more dynamic data sources are being utilised in ongoing projects.

Space-borne remote sensing data is expected to offer insight into urban land use and vegetation conditions on a significantly more frequent cycle and lower cost than conventional airborne surveying or site visits can offer. If, for example, the condition of urban vegetation is to be monitored, and this action is to be integrated into the digital twin, several things are needed. Firstly, the digital twin should include the vegetation features that contain the attributes needed to describe their condition. Secondly, the vegetation objects in the digital twin should be able to receive updates from an external system at semi-regular intervals, depending on the availability of satellite remote sensing data. Thirdly, new metadata should also be included, describing the topicality of condition information. Finally, we can also expect that new raster layers describing environmental conditions should be visualised with other relevant urban data sets and potentially also applied in further analysis.

In a similar manner, the developments in the mobility sector are creating pressure to better describe the mobility environment in urban digital twins (or in the 3D city models that act as their starting point). The updated CityGML 3.0 standard (CityGML referring to City Geography Markup Language), in particular its transportation module, appears to offer more means for this (Beil et al., 2020). Including the description of road network topology in an urban DT would allow the integration of mobility related data i.e. traffic volume of road segments with UDTs (Urban Digital Twins). Otherwise, many of the mobility-related applications and analyses may remain detached from cities' digital twins.

Roadside traffic monitoring sensors, such as lidars or edge-ai-cameras that produce near real-time data on individual vehicles and pedestrians also create questions regarding the updating frequency and aggregation of data. This also raises the question on whether and how such data should be tied to individual geospatial features of the urban digital twin. While there are existing standards that have touched upon this topic (OGC, 2016; Kutzner et al., 2020), in the context of urban digital twins, the widely used conventions are yet to emerge.

In addition to dynamic data offered by sensors, there is considerable interest in data either obtained from the users, or describing the users of the urban environment. Crowdsourced data on urban experience is gathered from defined groups of users, such as senior citizens, aiming to better understand their needs and experiences. In addition, the population data describing the citizens of urban areas are being increasingly integrated with urban digital twins, both as demographic and socioeconomic data. This creates potential and need for both enriching the existing DT features with new attributes, and form new features describing e.g. social hotspots in the city environment.

3.2 Social urban digital twins

Urban digital twins and social phenomena are gradually approaching each other. This is present in new DT data sources that arise from citizens themselves, analyses that focus on urban experiences and human perspective and user interfaces that present the digital twin to various stakeholders. This expands the applications of urban digital twins to other fields than traditional spatial planning. In city organisations, tasks like planning the provision of social and healthcare services have traditionally been carried out with the help of GIS data and analyses. However, this has not commonly been a part of urban digital twins.

Perhaps due to their 3D city modelling origins, the current examples of urban digital twins have been very much focused on the inclusion of quantitative data with urban features. If the digital twins are to be applied to social phenomena, increasing needs to also include qualitative data are emerging.

This implies that the tools for storing, classifying, clustering and visualising qualitative data have to be integrated with urban digital twins. Many of the current technologies and user interfaces aren't directly suited for this. In addition, the urban digital twins have to be made usable for people without prior experience in geomatics, if they are to be applied in supporting decision making in a broad range of tasks.

3.3 Modular urban digital twins

Interactive online 3D viewers are fast becoming the "default" viewport to the urban digital twins. In addition to visualising the data, various analysis functions are expected to support decision-making. This is to some extent driving the development of use-case-specific user interfaces and tools. At the same time, the ability to bring together different data and users remains a desired feature. Moving to a modular, networked approach in realising the urban digital twins appears crucial if both of these have to be achieved.

The same need for modularity arises from the increasing offering of commercially available data sources. Instead of seeing the urban digital twin as a technical centerpoint for gathering all urban data before it is then disseminated to different users, the digital twin becomes a network of different data sources, intermediate processing tools and user interfaces, applied in different combinations for different user groups (Figure 8).

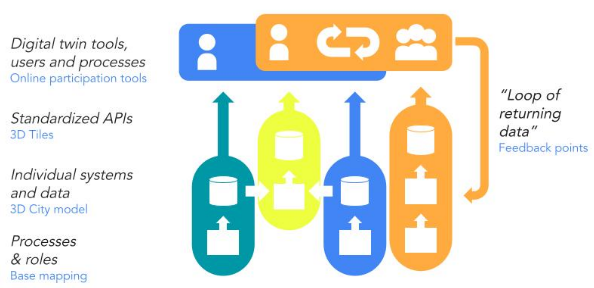

Figure 8. Thematic illustration of how an urban digital twin gathering citizen feedback is constructed by combining multiple data sources coming from different systems over APIs.

As the urban digital twins become modular, it is also apparent that there likely are more than one of them in a single city. Specific application domains may establish their dedicated digital twins that support their use cases, perhaps sharing some of the common data sources. For example, a dedicated digital twin may be developed to meet the needs of urban mobility management (see, e.g. Rinne et al., 2022).

Thus, transferability and usability of data across use cases and application domains becomes a vital factor for urban digital twins. This links the development of urban digital twins to the ongoing establishment of managed data spaces.

4. Conclusions

What are the central themes of development for urban DTs that arise from the ongoing projects? Clearly, the portfolio of data sources is expanding, and also beginning to include more frequently updated data sets and qualitative data. With the new data, urban digital twins increasingly begin to include information on other elements than just the man made components of the urban environment. This also begins to introduce the "social dimension" to urban digital twins, arising from the demographic and socio-economic data, crowdsourced data and tools that support participatory actions and decision making. In addition to different data, urban digital twins bring together different stakeholders and functions. As such, they possess many new opportunities but also require new ways of working and cooperation in their development.

As the amount of data sources and use cases grows, the urban digital twins become increasingly modular in their construction. Data from multiple open APIs are combined in different views that can be tailored to specific use cases. Thus, the urban digital twin is no longer a monolithic information system with a single online viewer, but a network formed from data sources, tools and user interfaces..

As the development of urban digital twins includes data collection, processing and utilisation it is not limited to visualising data layers, but connected with the entire chain of data production and use in the cities, including the creation of simulation scenarios, predictions etc. Therefore, the development of urban digital twins is intertwined with digitalization in cities.

Acknowledgements

The authors acknowledge the support from the following Horizon Europe projects: URBANAGE - Enhanced URBAN planning for AGE-friendly cities through disruptive technologies (No. 101004590), SPACE4Cities - Integrating Galileo and Copernicus downstream applications to support dynamic use of Public spaces (No. 101131955), SEDIMARK - SEcure Decentralised Intelligent Data MARKetplace (No. 101070074), ACUMEN - Ai-aided deCision tool for seamless mUltiModal nEtwork and traffic manageмeNt (No. 101103808), R4C - Regions4Climate (No. 101093873) and Spotted - Satellite Open Data for Smart City Services Development (Agreement number: INEA/CEF/ICT/A2020/2373501). The authors also acknowledge the support for Mobility Lab Helsinki, funded by the City of Helsinki's innovation fund (1/2022-12/2024). We also acknowledge the support from the AKKE funding instrument ('Supporting sustainable growth and vitality in the regions') for the DikaS project.

References

Beil, C., Ruhdorfer, R., Coduro, T., & Kolbe, T.H., 2020: Detailed streetspace modelling for multiple applications: Discussions on the proposed CityGML 3.0 transportation model. *ISPRS International Journal of Geo-Information*, 9(10), 603. https://doi.org/10.3390/ijgi9100603

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., Çöltekin, A., 2015: Applications of 3D city models: State of the art review. *ISPRS International Journal of Geo-Information*, 4(4), 2842-2889. https://doi.org/10.3390/ijgi4042842

Blumthaler, W., Bursa, B., Mailer, M., 2020: Influence of floating car data quality on congestion identification. *European Journal of Transport and Infrastructure Research*, 20(4), 22–37. https://doi.org/10.18757/ejtir.2020.20.4.5304

D'Hauwers, R., Walravens, N., Ballon, P., 2021: From an inside-in towards an outside-out urban digital twin: business models and implementation challenges, *ISPRS Ann. Photogramm. Remote*

Sens. Spatial Inf. Sci., VIII-4/W1-2021, 25–32, https://doi.org/10.5194/isprs-annals-VIII-4-W1-2021-25-2021.

Hyyppä E., Manninen P., Maanpää J., Taher J., Litkey P., Hyyti H., Kukko A., Kaartinen H., Ahokas E., Yu X., Muhojoki, J., Lehtomäki, M., Virtanen, J.-P., Hyyppä, J., 2023: Can the Perception Data of Autonomous Vehicles Be Used to Replace Mobile Mapping Surveys?—A Case Study Surveying Roadside City Trees. *Remote Sensing*. 15(7):1790. https://doi.org/10.3390/rs15071790

Hämäläinen, M., 2021: Urban development with dynamic digital twins in Helsinki city. *IET Smart Cities*, 3(4), 201-210, https://doi.org/10.1049/smc2.12015

Jones, D., Snider, C., Nassehi, A., Yon, J., Hicks, B., 2020: Characterising the Digital Twin: A systematic literature review. *CIRP journal of manufacturing science and technology*, 29, 36-52. https://doi.org/10.1016/j.cirpj.2020.02.002

Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W., 2018: Digital Twin in manufacturing: A categorical literature review and classification. *Ifac-PapersOnline*, 51(11), 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Kutzner, T., Chaturvedi, K., Kolbe, T.H. 2020: CityGML 3.0: New Functions Open Up New Applications. *PFG* 88, 43–61. https://doi.org/10.1007/s41064-020-00095-z

Lehner, H., Dorffner, L., 2020: Digital geoTwin Vienna: Towards a digital twin city as Geodata Hub. *PFG* 88, 63–75, https://doi.org/10.1007/s41064-020-00101-4

Lesani, A., Nateghinia, E., Miranda-Moreno, L.F., 2020: Development and evaluation of a real-time pedestrian counting system for high-volume conditions based on 2D LiDAR. *Transportation research part C: emerging technologies,* 114, 20-35. https://doi.org/10.1016/j.trc.2020.01.018

Li, F., Yigitcanlar, T., Nepal, M., Nguyen, K., Dur, F., 2023: Machine learning and remote sensing integration for leveraging urban sustainability: A review and framework. *Sustainable Cities and Society,* 104653. https://doi.org/10.1016/j.scs.2023.104653

Miller, R.B., Small, C., 2003: Cities from space: potential applications of remote sensing in urban environmental research and policy. *Environmental Science & Policy*, 6(2), 129-137. https://doi.org/10.1016/S1462-9011(03)00002-9

OGC, 2016. OGC SensorThings API Part 1: Sensing. http://www.opengis.net/doc/is/sensorthings/1.0

Rinne, J., Virtanen, J-P., Sahala, S., Kostiainen, J., Koskela, A. 2022: Digital Twin for Mobility - Concept and baseline study. Available online: https://mobilitylab.hel.fi/app/uploads/2022/09/Digital-Twin-for-Mobilty.-Working-paper-version-9-September-2022.pdf (Accessed on 12.4.2024)

Schrotter, G., Hürzeler, C., 2020: The Digital Twin of the City of Zurich for Urban Planning. *PFG* 88, 99–112, https://doi.org/10.1007/s41064-020-00092-2