How to Approach Technical Challenges in the Development of Urban Digital Twins: A case study of Tallinn, Estonia.

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Abstract. The processes of collecting, integrating, and representing heterogeneous urban data in Urban Digital Twins (UDTs) pose significant challenges. Besides, the lack of initiators' knowledge and experience may lead to severe consequences in the implementation, utilization, and maintenance of UDTs. This research identifies the challenges of UDT development in Tallinn, Estonia, and discusses the City of Tallinn's approaches as a case study. By analyzing the literature, the technical challenges related to the integration of heterogeneous qualitative and quantitative data for creating and updating UDTs (e.g., data collection, modeling, data integration, storage, and maintenance) have been identified, classified, and discussed with relevant officials of the City of Tallinn. Outsourcing data collection, using open-source software, and cloud computing were alternative solutions applied in Tallinn to overcome the challenges. The research concludes that initiators should clarify their objectives, expectations, and resources before developing UDTs to efficiently allocate and manage their technological and human resources to mitigate potential future obstacles.

Keywords: Urban Digital Twins, Collaborative Planning, Planning and Decision Support, Participation

1 Introduction

Urban planning involves a wide range of regulations and the consideration of different stakeholders' interests which make the process a complex undertaking. Today, with the contemporary advancement in technology, availability of large amounts of data, and computational capacities, innovative methods for planning processes are developed to deal with urban complexity while also allowing public empowerment and stakeholder involvement. Integration of all regulations and interests into the development process requires effective instruments to mediate diverse aspects and to support participation and collaboration processes throughout all urban planning stages. In this context, one of the beneficial tools can be the "digital twin", known as a digital representation that allows extensive data exchange and contains models, simulations, and programs that describe the counterpart's characteristics and behavior in the actual world (Deckert, et al., 2020). Urban Digital Twins (UDTs) are virtual replicas of cities that allow to simulate environments and develop solutions in response to urban, environmental, societal, and other challenges. In many cases, these tools can provide opportunities to evaluate alternative changes or predict future ones. Additionally, UDTs may serve as a tool to find common ground between divergent opinions and interests of urban stakeholders by enhancing public participation and understanding. This can support planning processes and lead to more livable and democratic cities, as well as strengthen the implementation of measures (Dembski et al., 2019).

However, the processes of collecting, integrating, and representing heterogeneous urban data in UDTs are challenging (Knezevic et al., 2022). Besides, making inappropriate strategies for the development of UDTs due to the lack of initiators' knowledge and experience may lead to severe consequences in the implementation, utilization, and maintenance of UDTs. Therefore, it is necessary for strategists, decision-makers, and other stakeholders to fully understand the potential challenges before initiating and developing UDTs.

This research aims at building a bridge between scientific and practical approaches to identify and address the challenges of UDT development with the case study of the City of Tallinn, Estonia.

To avoid unwanted consequences, it is critical to establish sophisticated processes in collecting, integrating, and representing heterogeneous data in UDTs such as catalog systems that contribute to overcoming the data integration challenge (Knezevic et al., 2022). Another essential factor is how to develop and implement data into a UDT that can address complex urban challenges in near real-time. Therefore, building, developing, managing, and maintaining UDTs requires the appropriate skills and human resources such as initiators, strategists, and managers, but also in-depth expertise from developers, programmers, computer scientists, and researchers from different fields.

Many researchers endeavored to provide a comprehensive overview of the challenges involved in deploying these tools. Lei et al., (2023) have identified and elaborated the challenges of UDTs in a literature review and Delphi method survey. They combined and categorized the findings into 14 technical and 9 non-technical challenges. Wang et al. (2023) have identified the difficulties associated with utilizing Digital Twins in smart cities and have suggested potential solutions as useful resources for the study and use of creating city information models in practice. Many other researchers have focused on several specific challenges. For example, cybersecurity risks are discussed by Adjei and Montasari (2023) as a critical aspect of the challenges that initiators have encountered when using UDTs. Another approach is investigating the modeling of urban infrastructure (e.g., road infrastructure, water supply, electricity supply, or public transport) in UDTs. For instance, Ferré-Bigorra et al. (2022) concluded the most comprehensive UDTs just modeled a specific aspect of urban infrastructures and do not encompass every aspect of it.

The focus of this study is practically investigating the approaches of Tallinn to overcome a selection of encountered challenges during the UDT development.

The objectives of this research are: Firstly, to comprehensively and critically comprehend UDTs' challenges. Secondly, to identify and explain the challenges from both academic research and industry, with a particular emphasis on practical considerations and insights gained from the experience of the City of Tallinn. Thirdly, due to the novelty of UDTs, making future initiators aware of the challenges they may encounter in the development process.

To reach these aims, the following research questions were formulated:

1. What challenges have been mentioned in prior studies, and how are they categorized and reported?
2. What is the City of Tallinn's motivation and strategy?
3. Which issues have emerged in the development of UDT of Tallinn and what was their approach to overcome them in practice?

To achieve these goals and answer these research questions, Section 2 describes the methodology. Section 3 reports the results. Section 4 discusses the potential UDT of Tallinn, its challenges, and solutions. Finally, Section 5 entails the conclusions.

2 Methodology

The present research employs a mixed-method methodology. The first step consists of a thematic analysis of the state-of-the-art scientific literature. This is done by snowball sampling, in which from the first selection of literature, related articles are reached by reviewing their references. In the second step, interviews with a relevant official of the potential UDTs of Tallinn were conducted to identify the challenges that Tallinn City is facing during their UDT development and the solutions they employed.

The scientific papers were selected based on predetermined criteria for inclusion and exclusion. We confined our focus to Urban Digital Twins (UDTs) specifically for communication and visualization. This led us to include papers encompassing 2D and 3D simulations, geo-based web portals, and game engines. We began with the recent related literature reviews and continued with the snowball sampling process.

Through an analysis of relevant papers and their reference lists, the challenges originated from subjects that came up regularly, and those taken more into consideration in the development of Tallinn UDT were reviewed either throughout the whole paper or in the related parts. Then, they are categorized and ultimately, these challenges have been discussed with the City of Tallinn's responsible person, Andres Maremäe, who has been the head of the GIS team from almost the beginning of the procedure of creating Linnamudel, which is one of the potential UDT of Tallinn, on which the focus lied during the interviews.

3 Results

The proposed study is more practical and strategic than philosophical. The major challenges encountered when attempting to create and update UDTs include how to collect, model, integrate, and simulate data and models.

Data quality and collection method: One of the first challenges many cities encounter is related to the question of which data is needed for creating a representation of a city. This entails not only the data content, data ownership, data format, data protection, and privacy but also the complexity and level of abstraction of data and above all understanding of what the data is needed. These issues include primarily the integrity and quality of data (Charitonidou, 2022). The quality of the data supplied to models in the digital twin, including data inaccuracies, dataset mistakes, poor sensor dispersal, etc. influences the accuracy of Digital Twins and keeps it from being an effective tool for data-based and informed decision-making and situation prediction (Nochta et al., 2021). Data quality is a critical issue, especially in participatory sensing and crowdsourced data, as human mistakes are common, and devices used by citizens (typically smartphone sensors) are not always calibrated. (Kim et al., 2019).

Data integration: Data integration is yet another significant obstacle, as emphasized by Gil (2020). This includes the heterogeneity of data, data relations, data categorization, data optimization, and the automatic updating of data. The heterogeneity of urban data, along with its various types and formats, hinders the immediate analyzability of the provided in smart city systems (Raghavan et al., 2020). Data lakes and databases' overabundance of information with the large volume of data gathered from the city makes it considerably difficult to evaluate such information in a way that is understandable to end users (Petrova-Antonova and Ilieva, 2019). The major challenge in data integration arises when data is collected from numerous sources as it lacks organization and structure, resulting in difficulties in distinguishing between accessible or restricted data (Ramu et al., 2022). Moreover, due to scattered devices and various systems, data integration demands the use of different configurations and techniques (Petrova-Antonova and Ilieva, 2019). Furthermore, some of the collected data are mostly fragmented. For instance, crowdsourced data, such as data from social and economic behavior (Shahat et al., 2021), and 3D geospatial data, e.g., point cloud (Labetski et al,. 2023), are not consolidated. Another vital data integration challenge arises in geospatial data when 3D models are combined with landscape models. This leads to the potential visualization of partly floating or lowering building objects or unknown subterranean depths may happen (Lei, 20..., Yan et al., 2019).

Interoperability and standards: Unified models, frameworks, and structures are essential for (real-time) data fusions, facilitating seamless connections between physical and virtual data sharing (Raes et al., 2021). This should be associated with the task of transitioning from a closed, static data model with iterative interoperability problems to a linked data model where the finished construction product can be completely depicted as a Digital Twin (Boje et al., 2020). Standards and guidelines play an important role in addressing the lack of universally accepted terminology for describing both real-world and virtual objects.

Digital Twins' linkage: The integration of multiple sub-components of a digital twin, or between multiple digital twins demands linkage to disparate databases in the UDT in an adaptable manner (Gil, 2020). For instance, different coordinate systems cause differences in the structuring and visualizing of data when integrating e.g. BIM into GIS data (Li et al., 2020).

Data conversion: Due to the heterogeneity of data that cities gather and its complex processing, suitable analytical techniques tailored to each data category are needed to enable the automatic transformation into quantitative data. One example of data conversion is integrating a macro- and micro-scale-built environment such as BIM and GIS and conducting data flow between these two platforms (Li et al., 2020).

Realtime updating: DTs should be updated regularly and if necessary, in real-time. The updating of the 3D city model, automatically generated from a newly collected LiDAR dataset, and its complete replacement of the previous model, along with the management of many variations of them, are challenging (Vitalis et al., 2019). On the other hand, urban sensors, such as IoT devices, which have been developed and applied rapidly in recent years, still face challenges such as access, data management, and unequal distribution across cities (Yang et al., 2022).

Visualization: Displaying the data in a way that is engaging and simple to understand for the user is another challenge. This applies to the user's experience and the appearance of the digital models, as well as the proper levels of realism and detailing.

Degree of Realism: Attaining the appropriate level of realism is crucial for enhancing the user’s experience of the surroundings. A difficulty lies in creating experimental expressions that are consistent with the related real space, i.e., integrating alternative expressions when photorealism is insufficient in one single model (Billger, 2017).

Abstraction of Complexity: A visualization that is too abstract, complex, and with many parameters may affect the understanding of the users (Wästberg et al., 2013). During the early phases of a planning process, excessive detail and visual realism in visualizations are frequently unnecessary and even deceptive or misleading, as certain information may not be agreed upon until later stages. Arising judgmental biases by prior experiences, intentions, and preferences as well as the “Wow effect” of a high level of realism could lead to an overly definite and nonnegotiable expression (Billger, 2017), which contradicts the concept of democratic decision-making.

Dynamic perspectives/viewpoints: The viewpoints should be altered to reach the best view, especially for measuring the distances. An aerial perspective can offer an overview but is unsuitable for providing the details required in the planning process (Wästberg et al., 2013).

Interaction with the models: The challenges are finding and connecting the appropriate instruments, managing a predetermined budget, and maintaining of display (e.g., VR head-mounted displays, screen projections, or individuals’ cell phones) and instruments for moving or navigating in the model (e.g., kinetics, eye tracking instruments, touch screens, or conventional mouse and keyboards) for a more comfortable and natural method of user's interaction.

Clear ownership: Uncertain ownership can lead to long-term data access problems (Petrova-Antonova and Ilieva, 2019). In the projects implemented through collaboration between researchers and urban planners, debates may arise concerning ownership and intellectual property rights, which further extend to influence the maintenance as well (Billger, 2017).

Accessibility: There should be a balance between suggesting unrestricted access for citizens to test scenarios and making a feeling of not influencing the planning process. This can be done by making restricted access to some changes in the planning application which also requires licenses in some technologies (Lei et al., 2023; D'Hauwers et al., 2021).

Cybersecurity: Cyberattacks on Urban Digital Twins can have serious consequences such as disclosing sensible information and taking over the system of critical infrastructures by unauthorized third parties. To specify data security, a comprehensive security assurance method and serious and open discussion are needed (Shahat et al., 2021). Such regulations make it possible to legitimize the procedure and strike a balance between the advantages of commercial information exploitation and social responsibility (Lei et al., 2023, D'Hauwers, et al. 2021). Moreover, significant amounts of DT data are in danger of exposure and sensitive data may be attacked in edge devices or while sending data to train models (Ramu et al. 2022).

Implementation: Determining use cases for individual contexts is the main factor that determines pertinent issues in the operation of digital twins (Lei et al., 2023). Implementation techniques that address urban planning, infrastructure optimization, and resource management must effectively leverage technology for the specific use case.

Interactive platforms, licensing, and computational power: Developing an interactive platform needs the special accessibility of software, specifically licensing. These platforms include websites, games, applications, or geo portals. The shortage of open-source software is one of the major problems since some technologies, especially software, such as CityEngine, often necessitate a license for offering advanced services. In addition, to guarantee that the entire synchronization process is not delayed, the cost and availability of computational power and human resources are significant concerns (Lu, Q. et al. 2020). Strategies should be defined based on the scale of the city.

4 Discussion

Tallinn has three main city 3D models which can be seen as potential Digital Twins. Those are Maa-amet developed by the Estonian Land Board (https://3d.maaamet.ee/kaart/), EHR developed by the Estonian Ministry of Economic Affairs and Communications (https://livekluster.ehr.ee/ui/ehr/v1/3d), and Linnamudel (https://gis.tallinn.ee/linnamudel/) developed by the City of Tallinn. The focus of this paper is on Linnamudel, which is a web-based potential UDT to give people a spatial understanding of the city's surroundings.

The model is being developed from a broader perspective for the public to a more professional one for decision-makers. The model's initial version is built based on data from the Tallinn base map (scale 1:2000), which is created, updated, and managed by the Tallinn GIS department.

In semi-structured interviews with the head of the GIS team, discussions were held about the identified challenges, their occurrence in Tallinn, and potential solutions to address them.

Tallinn outsources Data collection tasks and prioritizes the acquisition of data from external companies rather than investing in the deployment of drones, sensors, or other (IoT) devices. Tallinn cooperates with experts for the data collection through, e.g., remote sensing, satellite images, LiDAR data, and IoT sensors because the city's team is not specialized in these fields and lacks the capacity and technical equipment required. The city possesses one drone that the construction department uses to do checks on construction sites, but other instruments, such as IoT sensors, are provided by partners.

There are several examples of IoT sensor-based data collection applications in Tallinn. These include applications related to mobility, environment, building, metrology, and many others that can be reached at https://andmed.tallinn.ee/et/. Real-time data is integrated into this potential digital twin in some pilot projects, whereas access is restricted to city authorities. These projects encompass pedestrian traffic sensors in Tallinn’s old town, as well as energy consumption and internal air quality measurements from sensors. However, data collection remains incomplete in certain areas.

For instance, social media interactions are rarely collected typically only through the City’s Facebook account, and this data does not influence the city’s decision-making process. Although urban planners and sociologists use *Maptionnaire,* a platform for managing citizen engagement, the collected data is currently not connected to this potential UDT.

An exception is the pilot project “GreenTwins”, which harnesses the potential of UDTs to advance planning processes and democratic decision-making. This project enhances citizen participation by developing interactive tools for visualization and participation, as well as a city hub (Avalinn) in Tallinn's city center. Here, urban stakeholders such as citizens, planners, decision-makers, city administrators, businesses, and researchers can actively engage and communicate throughout the planning process. In addition, many UDTs lack the digital configuration of open areas and vegetation, a basic and distinctive component of cities. The GreenTwins project is currently developing and testing new urban technologies related to urban green digital twins and citizen participation/engagement (Caprari, G. et al., 2022).

The outsourcing approach to data collection may further complicate the data integration as the various data sets come from different sources. To address this issue, the City defined some interoperability standards and technical specifications. These outline how the data has to be provided with corresponding regulations. The City then directed its partners to supply the required formats, ensuring compatibility with the software used in the City. The technical description for the partners recently started and has some basic rules describing the APIs (Application Programming Interface), data structure, and the content of the data with more technical details. Furthermore, if special data is required and their partners are unable to provide it in the necessary format, the City utilizes additional software. For example, they use the Feature Manipulation Engine (FME) and adhere to common data standards for spatial data, such as those provided by the Open Geospatial Consortium (OGC), and sometimes even Esri standards.

The outsourced data are owned by the City and acquired through cloud services and just connect with Microsoft Azure as the central data platform and data warehouse of the city.

Data is streamed into Azure Hub as a cloud-based data repository, where subcontractors continuously upload information using their own, sometimes with their unique software. Then, the data which came from different sensors is converted and structured into a unified form. Afterward, the data is input into the ArcGIS application and this map application can visualize data on the 3D model e.g. Linnamudel.

Currently, the City's objective or focus does not lie in the establishment of a linkage with other digital twins, but they try to design a common data environment for different information systems. They achieve this by offering two options: Firstly, by manual data downloading and secondly connecting through APIs. For instance, they manually download LiDAR point clouds, which the Land Board provides once a year, and upload them manually to UDTs. They actually use these Point Clouds to generate the terrains in the Linnamudel. The other example covers LoD 2 building models, which are obtained from the Land Board databases through APIs.

Considering the scale of Tallinn, currently, they do not engage in compressing or optimizing processes, as their data sets are not large enough to require such measures. Likewise, data storage is not an expensive part of Tallinn's potential UDT. To categorize their data, they employ a basic categorization solution, which differentiates between spatially enabled data and non-spatially enabled data. When the City of Tallinn designed its common data environment, it made some decisions, such as how to categorize data and what kind of data should be kept on their servers, and which can be stored on cloud-based servers. The decision-making process is governed by stringent security and data privacy regulations of Estonia and the European Union. These laws provide specific criteria for data storage, including geographical restrictions, e.g. certain data being prohibited from storage outside the EU.

The transformation of data within the City's system often necessitates modeling activities and the development of algorithms capable of extracting or aggregating information. For example, they create digital terrain and elevation models out of ArcGIS (Esri software) and generate buildings out of the point cloud by using this software. This means that they do not develop their own software but use tools that already exist. However, the head of the GIS department recommends employing in-house software developers for affording more flexibility, innovation, and greater creativity within UDTs development, albeit at a higher cost. Regarding big data, they are hiring one machine learning specialist to specify their partners' tasks who are in charge to find out how to order the required services for big data that should be handled by machine learning or AI e.g., remote sensing or laser scanning data. The City uses mobile data capture methods through point clouds, then their partners analyze the point cloud to identify e.g., road surface defects or urban green elements.

Regarding the level of abstraction in information visualization and the utilization of symbols or colors, they make selections on what to display in Linnamudel. The data must meet quality standards for inclusion. This is a subjective decision and may be decided by the 3D specialists responsible.

Table 1. Summary of the discussed challenges and the City of Tallinn's approaches and solutions to overcoming them.

Challenge	Tallinn approach / solution
Data collection	Outsourced to external companies. Hired a machine learning specialist
Data integration	Acquired through clouds with pre-defined rules and stored in Azure hub
Interoperability	Data should be provided only with corresponding standards by partners
Linkage	Two options: 1) manual data downloading 2) Connection through APIs
Data conversion	Data from different sources is converted and structured to a unified form. Sometimes it is done by additional software e.g., FME
Real-time data	Currently tested in pilot projects, restricted access to City authorities
Visualization	Web-based and in the city hub (AvaLinn) via projection and the possibility of using shutter-glasses (3D) as well as on screens
Degree of Realism	Subjective decisions are taken by the responsible 3D specialists
Abstraction	3D specialists make the selection on what to include or exclude
Ownership	City owns data and uses the Esri software to visualize on Linnamudel
Accessibility	Modification is restricted, the challenge is how to activate business owners to use the Linnamudel
Cybersecurity	European and Estonian strict security and data privacy legislation must be followed
Implementation	For urban planning, citizen participation, and collaboration processes
Platform	Web-based platform powered by ArcGIS (Esri)

One additional challenge in the application of Linnamudel is finding ways to encourage business owners to utilize digital twins. As Head of the GIS team at the City of Tallinn has mentioned, another challenge in practice is changing people's habits, as related business employees would rather continue their traditional work than work with digital tools.

5 Conclusion

Urban planning needs to create reliable digital settings for overcoming the complexity of urban data, communicating with stakeholders, and comprehending future scenarios. The challenges of data integration, visualization, and utilization of UDTs may hinder the appropriate application of these tools and hence, create new challenges for urban planning. Therefore, strategists and developers should define their particular aims for developing UDTs before considering the choice of the required hardware instruments, human resources, and software to avoid the waste of various resources.

To achieve successful implementation of Urban Digital Twins, each phase and aspect - including data collection, integration, development of digital models, and interoperability - must be managed by either the initiators and their in-house software developers or external partners.

Developers and decision-makers should carefully consider factors such as the scale of the city, expectations, and regulations before choosing an approach or taking a decision. This includes decisions related to internal or external data collection, whether to invest in new instruments and internal software development, or to utilize existing tools from external partners, and whether to opt for in-house or cloud-based data storage.

Although the development of UDTs has been the primary emphasis of this research, our findings are generally applicable to city models at different scales. Finally, it is crucial to remember that involving businesses in utilizing UDTs and changing people’s habits can make an advantage for both UDT development and the City. For a more comprehensive understanding of the subjects in question, particularly pertaining to Tallinn, additional research must be undertaken. This investigative approach will allow for a more detailed exploration of the specific phenomena and underlying principles.

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