Comparative Analysis of Digital Twins in Smart Cities

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Abstract

Digital twin is a rising market in both, public and private sectors. Many city projects, like Herrenberg, Rotterdam, New York, and Connected Urban Twin (CUT, in Germany) develop digital twins to explore their possibilities and improve the quality of life in the city. In this paper, we review literature on smart city and digital twins to build the scientific knowledge base and to provide an understanding of these concepts. Subsequently, a comparative case analysis is conducted to compare the cities' digital twin projects regarding their project focus, budget, data, (data) architecture, used technologies and citizen participation. Rotterdam provides an openly available 3D model along with research data standardization, interoperability and connected urban twins. While Herrenberg focuses on a participative collaborative planning process, New York focuses on the use of AI. The results indicate that the projects face challenges regarding data standardization, interoperability, and visualization. Yet, interoperability and data handling are particularly crucial for the implementation of a digital twin and for leveraging the relevant data. Future research should investigate best-practices and challenges in a more comprehensive way.

Keywords

Digital Twin, Smart City, Data, Stakeholder

1. Introduction

Digital twins' (DT) relevance is increasing, particularly in areas like automotive or aviation [1]. Its market value of 8.6 billion US-Dollar in 2022 is expected to grow to 137.67 billion US-Dollar in 2030 [2]. A survey by the CIO Magazin states that 13% of 600 enterprises use a digital twin, and further 62% plan to introduce such [3]. Digital twin technology is also used in the public sector, as virtual representation of entire cities or urban areas [4]. The virtual representation and simulation of objects, factories, houses or even cities can help to solve real-world problems [5] [6]. In Smart City, digital twins are combined with Internet of Things (IoT), Artificial Intelligence (AI), speech capabilities and augmented reality (AR) [5].

The aim of this paper is to describe and compare four DT cases (Rotterdam, Connected Urban Twins, New York and Herrenberg), which develop digital twins to virtually represent a city as a whole or a part of it. We aim to investigate what types of data and what mechanisms of DTs are used, and what lessons can be drawn from the cases for other DTs to build on this knowledge.

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The work is structured as follows; section 2 introduces the research design. In section 3, the foundations of "smart city" and "digital twin" are explained. Section 4 introduces the four cases, which are evaluated and compared along the method of Bartlett and Vavrus in section 5. Section 6 introduces a future scenario along the six smart city fields. We conclude in section 7 with a summary of the findings, and with limitations and future research.

2. Research Design

The theoretical foundation is built by a systematic literature review according to [7]. The databases from IEEE Xplore and web of science are used. Parisfal [8] is used to organize the literature review. The search string derived from the research objectives is: *(("digital twin" OR "3-D Model" OR "counterpart" OR "digital model" OR "digital shadow" OR "virtual model") AND "smart city").* To include an article for the study, it must be written in English or German language, and it must be a conference proceeding or journal article. Additionally, the abstract must indicate that the whole article is about digital twin in smart city. Grey literature, work in progress and duplicates as well as articles, where the abstract does not cover digital twin in smart cities, are excluded. The quality assessment of papers includes five questions: 1. Are research objectives or research questions clearly defined? 2. Are digital twins (DTs) discussed/defined in the context of smart city? 3. Are use-cases presented in the context of DT in smart city? 4. Are best practices presented in the article? 5. Are limitations discussed regarding the validity of the results obtained? The questions are answered with "yes" (1 point), "partially" (0,5 p) and "no" (0 p). Articles with four points or more are included in this research. In total, 1.236 articles were found, of which 57 papers are selected. After removing duplicates, 47 articles remain for the quality assessment, of which finally eight are included in this article for the foundational research. A manual search is conducted for the definition of smart city. Additionally, grey literature is used to describe the case studies, including (project-)documentations, white papers, websites, and newspapers. For the comparative case analysis, the methodology of Bartlett and Vavrus [9] is utilized to systematically compare the digital twin projects regarding their smart city field and focus, budget & funding, used technologies, used data, (data) architecture, stakeholders, and citizen participation.

3. Foundational Understanding of Smart City and Digital Twin

Along the systematic literature review, key terms such as Smart City and Digital twin were studied and are explained in the following.

At the beginning of the last century just under 13% of people lived in cities. In 2050 almost 80% of the people are expected to live in cities, giving importance to the development of a smart city [10] [11]. Mehmood argues that "*the field of smart city is highly interdisciplinary and requires coordinated efforts from all the stakeholders*" [12]. Possible stakeholders include planners, administrations, residents, companies and more [12]. Nam and Pardo argue that "*a smart city should envision smart economy, smart governance, smart mobility, smart environment, smart people, and smart living*" [13]. [14] add management, organization and policy context.

In literature, no uniquely agreed upon definition of smart city exist [13][15][16][17]. Related terms include digital city, intelligent city, ubiquitous city, etc. [13] [17]. The focus in these terms is a technologically developed city [18][19][20]. However, a smart city encompasses much more than just technology as indicated in the above understanding of [12]. Kozlowski divides the term smart city into four orientations: technology, institutional, human and hybrid orientation [17]. *Technology* focuses on the use of technical infrastructure to improve quality of life. *Institutional* aims to promote initiatives for the environment, the economy and social life. *Human orientation* aims to improve teaching, research, and knowledge of a city, enabling the inhabitants to live their own lives. The *hybrid orientation* combines the three areas, resulting in a sustainable and effective city. Thus, the investment in a more developed city is an investment in human and social capital [17]. The goals of a smart city include reducing the ecological footprint, advancing solutions for a smart mobility, as well as the efficiency of urban management [21][22].

Smart cities produce data, which are the basis of a DT [23]. The term digital twin was first defined by NASA in 2010 as "*an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin*" [24]. Since this definition, scholars came elaborated own definitions, mostly describing DT as a digital or virtual representation of a physical counterpart like an object or city [6][25][26], and using related terms like digital shadow [26], 3D model [26], virtual or digital model [27], and counterpart [27]. No unified definition exists, though [25][27][28]. VanDerHorn and Mahadevan performed a review of 46 definitions and concluded the understanding of DT as: "*a virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems*" [28]. The exchange of information is process- or context-dependent. It can happen after a few milliseconds, a few days or even a few weeks [28].

4. Introduction to the four Case Studies of DTs

Four cases have been selected for a comparative analysis: Connected Urban Twin (CUT), New York, Herrenberg and Rotterdam. Criteria for selection have been the size and location. Herrenberg is chosen because it is a small town in Germany. CUT is chosen because it covers three "bigger" cities in Germany (Hamburg, Leipzig and Munich). Rotterdam serves as the medium sized city in the near European neighborhood, and lastly New York is the biggest city chosen and the "outsider" in the U.S. Therefore, covering Germany as a central point of comparison as well as an EU member state and an American city to cover an alternative approach with different regulations and funding.

4.1. Connected Urban Twin (CUT) in Hamburg, Leipzig and Munich, Germany

CUT consists of three cities, Hamburg, Leipzig, and Munich [31]. Hamburg is the second largest city in Germany with 1.9 million inhabitants [32], Munich has over 1.5 million inhabitants [33], and Leipzig counts around 630,000 inhabitants [34]. The CUT project runs from 2021 to 2025 with a volume of €32.4 million. It is funded among 73 'model projects smart city' by the Federal Ministry of Housing, Urban Development and Building [35]. The CUT project team sees a digital twin as a construction kit, which can consist of various building blocks. These building blocks can be arranged differently depending on the requirements and circumstances of the respective city [36], including physical objects, logical structures, and other data about the respective city. The stakeholders of the city are also part of the twin [36]. Digital data form the basis for CUT. Creating a digital twin using available data follows a procedure. The geo-basis information, which defines the object to be digitized, is recorded. It can be used to map the spatial environment. Once the spatial delimitation has been completed, the specialist data, i.e. application-specific data, is collected. This data helps to assign properties/benefits to certain locations, e.g. for environmental protection. This data is analyzed, if reasonable with AI support. Applications are made available as an interface, so that people can interact with the data. Finally, a geospatial twin is created, which has access to the recorded geo-data and specialist data. Users can analyze and display the geospatial twin in the applications [37]. In addition to the geospatial twin, there are many other twins for different use cases. The geospatial twin is a central twin that coordinates other twins and processes, and it has a broker functionality [36]. Ultimately, users are able to ask a question using the application. The application accesses the twin and picks out the required modules that are necessary to answer the question [31]. While many other initiatives are subsumed under CUT [31], our paper focuses on DTs in CUT.

4.2. Digital Twin in New York, USA

New York has around 8.4 million inhabitants [38] and is located on the east coast of the United States. The interdisciplinary team at Columbia University has developed a digital twin of New York City that uses sensor data and machine learning to optimize traffic flow and traffic safety [39][40]. The aim of the project is a hybrid twin. It shall serve a better traffic management system. To achieve this goal, the researchers use COSMOS as next generation communication network, AI and edge cloud computing. The hybrid twin consists of a physical simulation and a digital twin. It contains physically based models, a virtual scenery, and sensors to analyze and predict road traffic [39]. The team worked mainly with literary, which contributes on topics of data analytics and machine learning [41]. The digital twin is observed and run in the "NSF PAWR COSMOS city-scale wireless testbed". COSMOS is located next to the Columbia University campus [42]. The project sets up a fast network with bandwidth and low latency, which is suitable for carrying out experiments in the real world, such as traffic management at a busy intersection. At a large intersection in New York, the sensors can identify around 80 moving objects in just one moment, which includes cars, pedestrians and bicycles [42]. With the help of COSMOS and suitable sensors and technology, many objects are detected and analyzed in a short time. Based on this data, AI is trained to understand and predict certain scenarios in the DT in the future. Among other things, this can result in more efficient traffic light control [42].

4.3. Digital Twin (3D model) in Herrenberg, Germany

Herrenberg has 32.649 inhabitants [44] and is part of the Stuttgart metropolitan region in Baden-Württemberg [45]. In 2022, Herrenberg approved their guiding principles until 2035, which aims to improve 17 objectives to reach a sustainable city development [46]. The City cooperated with Fraunhofer IAO Stuttgart, High-Performance Computing Center Stuttgart

(HLRS), the University of Groningen and the University of Stuttgart to develop a digital twin [45]. The partner HLRS was funded by the Ministry of Science, Research, and the Arts Baden-Württemberg as part of the "Living Lab: City Districts 4.0" [47]. The funding of around €8 Mio. was dedicated to eight projects, of which Herrenberg is one. Following a human-centric approach, Herrenberg aims at improving the quality of life for its citizens [45] with the use of a 3D model. The first launch of the 3D model was in 2017, providing a virtual representation of the city center, and later also including cars, busses etc. [45]. In 2019, test sensors were deployed to collect environmental data, while citizens could provide their cycling and walking data through an app. The sensor and app data are integrated in the DT to provide an air flow simulation (pollution particles in the air) and a street network to improve the routing of cars or pedestrians. To distribute the data, a data flow was constructed (see Fig.2 in [45]). Integrated data are sensor data, geographical data, social data, pictures of buildings, laser scan data, and app data. Survey data are not directly integrated into the DT. In 2022, the digital twin prototype was demonstrated at a city-event [48] to engage with citizens by providing a stationary Cave automatic virtual environment. The result shows that 95% of the respondents of a survey perceived the visualization to have a positive effect on local planning and participatory processes [45]. The authors argue that 3D models can be used in participatory urban planning processes to visualize complex problems in a less complex model so that non-experts can understand the situation [45]. The authors argue further that the results have yet to be validated and should be used with caution. For this, a next project is initiated in Herrenberg [49].

4.4. Digital Twin in Rotterdam, Netherlands

Rotterdam has 664.071 inhabitants and possesses the largest port in Europe [50]. The city is part of two projects funded under the European Union´s Horizon 2020 funding scheme. The Ruggedised project aimed to demonstrate "*how to combine ICT, e-mobility and energy solutions to design smart, resilient cities for everyone*" [51] [5]. It was located in the south district of Rotterdam and finished by end of 2022. The port of Rotterdam is part of the EU-funded project MAGPIE (10/2021 to 9/2026), which aims to investigate "*alternative energy sources, smart technologies applied to power operations and river and rail connections with the hinterland*" [52]. Both projects include the development or extension of a digital twin. For the extension of the 3D model of Rotterdam in the Ruggedised project, it is extended with an operations platform. Available open data of the district is visualized in a 3D platform [53]. With the visualization it is "*possible to monitor and communicate different information (starting with the energy performance of buildings), enabling endless applications and scalable to digital city level*" [56]. The project partners expected a decrease of the energy consumption of 82000 kMh, which is equal to a 41 tons reduction of CO_2 [51]. In a second Proof of Concept, open data standards and real-time data, owned by the municipality, but provided by private data sources, were tested. The architecture consists of a data hub as central unit, connected to an open data marketplace, data intelligence & decision support tool, the 3D information- and communication platform and it is connected to the LoRa cable and Wi-Fi etc., collecting sensor data [51]. Lessons learned in the Ruggedised project are: (1) The municipality does not want to be the owner of data, but the end user; (2) No agreements on data formats or transportation were made; (3) The use of open data is more difficult than the actors expected; (4) Not all open data standards are accessible or easy-to-use [51]. The ongoing MAGPIE project has so far developed the digital platforms & services for port operations [54] and a definition of a modular architecture for the port digital twin [55]. For the digital platform and services, the port authority of Rotterdam "*already has a digital twin for monitoring maritime conditions, namely tides and water conditions*" [54], but it also explores semantic models, like ontologies, to integrate heterogeneous data from multiple sources to represent more of the port operations. Interoperability between the port actors needs to be ensured and there is a need to develop digital tools for decarbonization and green logistics operations [54]. According to Bouter et al. the port DT consists of three main components, the data sharing architecture, the language specification and the tools and systems. Rotterdam follows the European Data Strategy to create a common European data space, with a focus on a port digital data environment enabling a controlled discovery and sharing of potentially sensitive and valuable data [55].

5. Comparative Case Analysis of the four DTs

The four DT cases are compared along the following aspects, following the methodology of Bartlett and Vavrus [9]: (1) Focus/Smart City field, (2) Project budget/funding, (3) Used data, (4) (Data) Architecture, (5) Used technologies and (6) Citizen participation. The analysis is conducted first by the researchers individually, and then the assessments and findings are discussed together. Results are presented below and summarized in Table 1.

Starting with the *focus of the projects* (1): Herrenberg and CUT are similar as they focus on a sustainable city development, while Rotterdam and New York both focus on smart mobility. The *project budgets* (2) differ in each project, while for New York there is no budget publicly available. Herrenbergs funding is a part of €8 Mio., because this amount was dedicated to seven projects. Only Rotterdam and CUT provide their budgets, Rotterdam´s Ruggedised project had a budget of around 19.3 Mio. Euro and was funded with around 17.7 Mio Euro. The MAGPIE project in Rotterdam, has a Budget of €32.4 Mio. and is funded with €25 Mio. CUT has a similar budget to the MAGPIE project with around €32.4 Mio Euro and a funding of €21 Mio. (3) All projects *use data* provided by their sensor network. Herrenberg and CUT both use geobasis information for the development of their DT. Herrenberg is the only city that uses citizen data in form of routing data from volunteer cyclists or pedestrians that want to help. Rotterdam additionally uses supply chain, energy and air pollution data. CUT involves specific application data, like climate, traffic, geo and building data. New York and CUT have traffic data and video data. (4) Their *architectures* differ, while also having similarities such as the DT and connected Data spaces, sensor networks and context specific applications. The difference is that in the CUT project, several DTs are connected to each other performing different functions (building, geobasis, demographics). For Interoperability the MAGPIE project in Rotterdam is researching ontologies to be able to connect and transport data between all platforms and DTs across countries. For their used *technologies* (5), all projects employ sensor networks to provide a data basis, while the projects transmit and store data differently. Furthermore, all projects use 3D models. Rotterdam and CUT use Data Spaces and Platforms to store their data. Rotterdam additionally builds a data marketplace.

Table 1:
Comparison of DT projects in Rotterdam, Herrenberg, CUT and New York

Category	Herrenberg [46]	Rotterdam [51][52]	CUT [31][36][37]	New York [39][40][41]	Synthesis
(1) Focus	Sustainable city develop-ment	Smart mobility & Green ports	Sustainable & inte-grated city develop-ment, smart mobility	Traffic management	Similar focus
(2) Budgeting	Part of 8 Mio €	19.3 Mio. € 30.7 Mio €	32.4 Mio. €	Not available	Different Budgets
(3) Used Data	Citizen, Geo, Sensor	Sensor, Energy, Air pollution, Supply Chain,	Geo specific application data	Video, Traffic	Different kind of data
(4) Architecture	DT & Case specific applications	DT & data space & data marketplace	Connected DTs	Sensor net-work connec-ted to AI	Different approaches
(5) Technology	Simulations, Sensor net-works, HPC	Simulations, Sensor network, Data Spaces	Simulation, Sensor network, Data platform	Simulation, sensor network, AI, camera	Simulations & sensor net-works used in all project
(6) Citizen participation	High	None	Moderate	None	Engagement differs

New York is the only project using AI and cameras. While the projects differ in their approach to develop a DT, similar aspects like sensors, sensor network, data standardization, data storage and interoperability are emphasized by all. The *citizen participation* (6) is of great importance for Herrenberg and CUT, as the cities include the citizens in the process. Herrenberg includes them as data providers or do live demonstrations to engage with the citizens. CUT is developing an academy to engage with citizens in webinars. CUT has a dedicated subproject 'participation' of the municipal corporation. Rotterdam and New York do not engage with citizen directly.

Beyond citizen participation, different types of stakeholder engagement are utilized, like meetings, workshops, surveys, interviews, live demonstrations and co-creation. The different stakeholders who interact with a smart city have an influence on or benefit from the digital twin. The various stakeholders can be divided into different groups: (1) Public authorities are responsible for strategic and, in some cases, operational planning. They are also the administrators of the DT. They either commission private companies to create a (part of a) DT or they create one themselves, involving substantial personnel and costs. In the CUT example, all are city authorities, plus the federal authorities subsidizing the project. (2) Citizens are the residents of a city. They are one target group and end users of a DT, which e.g. can provide an overview of the traffic or a weather forecast. (3) Companies are an important part of a city, not only as employers, but also as providers of relevant services, such as the development of certain areas of a DT. Companies can also use digital twins themselves to predict future scenarios, like supply chain management. Some public companies, like public transportation companies (4), use smart mobility solutions, which in turn provides data for the DT. This also includes energy suppliers (5), who must ensure that the infrastructure is distributed fairly, efficient, and sustainable to all parts of the city. The same applies for wastewater and waste management. IT and telecommunications companies (6) receive special attention in the field of the DT as they offer the underlying IT infrastructure and the network for fast data transmission. (7) Environmental protection organizations may also be involved as (8) research institutes and educational institutions. The research institutes often provide new advancements of development of digital twins and the underlying concepts, standards and frameworks or develop them in a joint effort. They also carry out studies and develop innovations for use in the projects. In addition, they are not only part of the development, but also benefit as users if they want to depict realistic scenarios with the help of the digital twin and validate those outcomes.

Based on the insights from the comparative analysis of the four cases, we next depict a future scenario with the aim of integrating many of the different features of DTs.

6. Future Scenario for a Comprehensive DT

There is currently no known digital twin that maps all fields of a smart city. While, a digital twin should simulate real-world objects and processes in a virtual world, a DT can help a city also to elaborate predictions about certain scenarios in the future, e.g. in operations and transportation management. To map all areas of a smart city, a number of additional sensors need to be deployed to collect data. Along this, requirements of data protection and data security must be followed, e.g. Art. 22 of the GDPR of the European Union, which prohibits automated decisions. Furthermore, attention must be paid to up-to-date data and quality, as well as to a well-developed network infrastructure such as COSMOS [42]. The infrastructure serves as an interface between the various applications and is intended to increase interoperability, which requires a common data standard as well. To address all these challenges, we depict a future scenario based on the scenario technique described in [43].

The vision of the scenario is depicted in Figure 1 and is outlined as follows: Assuming the above requirements are met and challenges resolved, AI receives data directly from the IoT sensors, which are recording e.g. pedestrians and cars crossing a junction. AI creates future scenarios based on fast-computing power of the DT. The DT can be used in any city and encompasses every smart city field indicated in Nam and Pardo [13]. The benefits of DTs are sustainable urban development and a positive impact on the ecological footprint. Furthermore, processes are digitized and simplified. In this way, valid forecasts can be made with substantial positive impact on the quality of city life. In addition to IoT sensors, the stakeholders in the city (e.g. companies, residents, NGOs and the administrations) produce and record data. Once recorded, the data is forwarded to the servers via a fast, latency-free network. A highly secured cloud-based AI is implemented on these servers, making it accessible from anywhere for the users. Through structured and standardized databases and data lakes, the implemented applications can access, analyze and process the data effectively. A high level of interoperability and a functioning IT-infrastructure are available for the development of the DT. The AI can create individual digital twins that are adapted to the user's requirements. This closes the circle, as the digital twin created quickly communicates data back to the stakeholders. The future scenario gives twelve examples of where DTs can support. Ultimately, all these aspects, in their combination, are of great importance to enable a positive impact in a city. It is therefore important that all stakeholders work together for a better city in such a future scenario (see also the "hybrid orientation" by Kozlowski [17]).

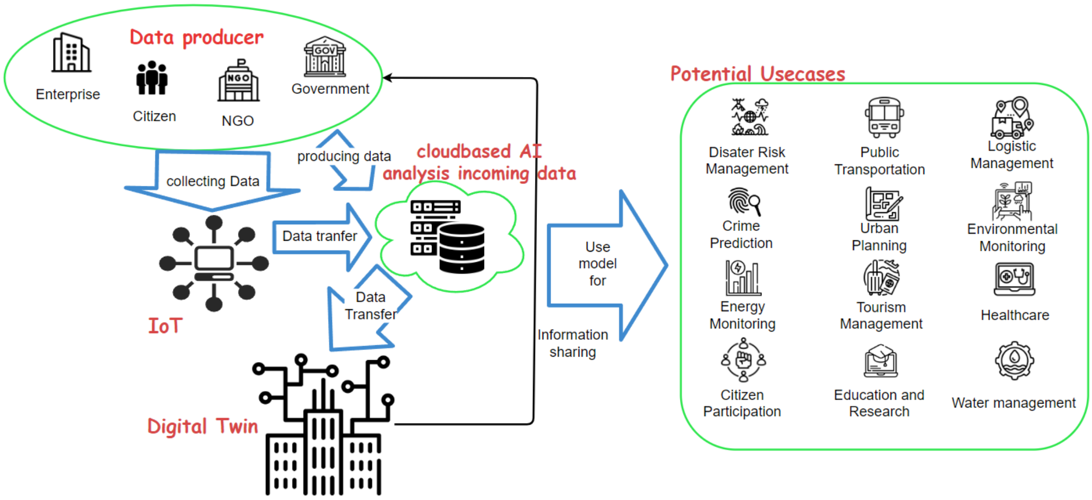

Figure 1: Future scenario showing dataflow and possible use cases of a comprehensive DT

7. Conclusion

This paper investigated the concept of digital twins and compared four digital twin projects from Herrenberg, Rotterdam, Connected Urban Twin (Leipzig, Munich, and Hamburg), and New York regarding their project focus, budget, used data, (data) architecture, technology and citizen participation. It identified important aspects and challenges for the development and implementation of a DT. To reflect on our research objectives and driving questions, the comparative case analysis methodology was applied to analyze and describe the projects, and to synthesize the comparison and derive lessons learnt. Rotterdam is an advanced city because it is the only city having a 3D model openly available after finishing a project. In contrast to this, Herrenberg developed a prototype, but not an openly available DT. The other projects do not have anything relatable yet. Also, Rotterdam is facing the problem of missing data standards and interoperability concerns. To meet these challenges, Rotterdam is developing a data space in line with the European data strategy. The CUT project develops reusable building blocks for other cities to create their own urban data platforms or digital twins. Herrenberg and New York are missing a clear strategy to handle data and to integrate them into their DT. Thus, Herrenberg and New York may use the findings of Rotterdam and CUT to build their data platform and DT.

The high citizen involvement in Herrenberg and CUT enables the citizens' voices to be heard and to make the projects visible. New York and Rotterdam do not engage with citizens visibly and could learn from the participatory process from Herrenberg. All projects demonstrate the need for substantial stakeholder engagement. However, this requires time, personnel and capabilities of engaging with the stakeholders.

The four cases represent different implementations of digital twins. While there is substantial potentials of DTs for improving the quality of life in urban areas, further research and development is necessary to leverage their full potentials as shown in the visionary scenario of DTs in smart city development.

The research conducted also comes with limitations. Due to the limited space for the conference paper, the literature analysis is substantially compressed. The comparative analysis covers four projects with different project focuses. This is because of the given time and constraints of the research. Further research will need to complement the study with further cases, also beyond Europe and North America.

Many findings like data spaces, data standardization, interoperability, CUT´s reusable data platform and DT building blocks, and the question of data ownership are relevant for DT and smart city projects, especially in the EU. Future research needs to investigate data governance, best-practices and challenges amongst digital twin implementations so that other projects can learn for their initiatives. Future research should also investigate the impact and added value of DTs in smart city and smart governance settings, and in particular for their stakeholders.

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