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Urban development with dynamic digital twins in Helsinki city

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Abstract
A dynamic digital twin is a feasible solution that can be employed to build real-time connectivity between virtual and physical objects. Industries like manufacturing, aerospace and healthcare utilise dynamic digital twins for simulation, monitoring and control purposes, but recently, this nascent technology has also attracted the interest of urban designers. Due to the novelty of the dynamic digital twin in urban design, this research study addresses the concept of digital twin technology and investigates its applicability in so-called smart city settings. Drawing on results from research interviews and examples from the Digital Twin project in Helsinki city, the research illustrates that solid data infrastructure forms the foundation for urban digital twins and the development of future smart city applications and services. Furthermore, data-enriched digital twins evidently accelerate smart city experimentations and strengthen both learning and knowledge-based decision-making. Digital twins have also proved that they offer an environment in which smart city practitioners can bridge multi-stakeholder urban design teams through one digital platform.

KEYWORDS
Digital twin, smart city, smart city experimentation, stakeholders

1 | INTRODUCTION

Globally, cities benefit from advanced digital technologies upgrading city infrastructures and functions and also building new digital services that can facilitate the lives of citizens. With nascent digital technologies like the Internet of Things (IoT) and artificial intelligence (AI), cities aim to optimise their daily functions (e.g. traffic and energy consumption). Alternatively, by investing in digital technologies (surveillance cameras and sensor technologies), cities aim to also strengthen city security and enhance the overall monitoring and governance of cities. Moreover, with novel digital technologies, cities aim to synchronise city processes and attract citizens to participate in urban development projects and activities. By doing so, cities pursue making city operations more transparent and less bureaucratic for the citizens [1–6].

Considering climate change and environmental impacts, cities have a salient role when adopting and carrying out sustainability initiatives. According to [7]; cities globally are responsible for over 75 percent of the world´s energy and material flows and consumption. It is emphasised that understanding cities´ urban metabolism (the production, import and export of diverse natural and non-renewable material flows like water, energy, food and waste in the urban area) is fundamental when developing more sustainable cities and communities [8–10]. By exploiting smart city technologies, including dynamic digital twins, cities may enhance the design and planning of urban metabolism and improve possibilities to simulate alternative solutions in a virtual environment before final implementation. Novel digital solutions thus assist cities in optimising urban metabolism and find solutions with which to achieve the climate change and sustainability objectives set for the cities.

Following the development of computer-aided design (CAD), urban designers have utilised digital three-dimensional (3D) modelling to construct static 3D city models of the built environment and also to bring content to digital city models. Static 3D city models have allowed urban developers to visualise and analyse city plans and allowed urban developers to communicate the plans more easily to other city developers [11, 12]. However, recently the evolution of digital technologies, the emergence of sensors and the IoT have taken virtual 3D modelling to the next level. Following examples from reference industries, such as mechanical engineering and aerospace, designers implement sensor technologies to form connectivity between a static 3D model and its real-world physical counterpart. The possibility to integrate data (both real-time and/or historical data) in the static 3D models has enabled designers to engender *dynamic digital twins,* which allow for observing the object simultaneously in its real and virtual environment. Indeed, a dynamic digital twin is commonly used during product and production design phases to simulate, monitor and control, for example, manufacturing processes and facilities [13, 14].

For the same reason that the concept of a dynamic digital twin is a relevant and well-adopted solution in industry, it also appears to be a prominent and emerging technology in urban development projects [15–18]. Since digital twins are a relatively new and emerging technology in urban development and in smart city discourse, this study is positioned to explore a digital twin´s applicability in smart city settings and to learn about the experiences and conditions in which the concept of a digital twin is applied in an urban design context. The theoretical insights of the study draw on the concepts of the smart city and digital twin technology. The practical implementation of the study draws on interviews and the official project reports of the Helsinki Digital Twin project to illustrate how the concept of a digital twin is utilised in diverse urban development projects in Helsinki.

The study contributes to existing smart city literature by denoting a digital twin as a prominent concept for improving the design, governance and management of urban development initiatives. It also contributes to conveying the cognitive aspects, knowledge and learning of the city [19] and considering quadruple-helix (academia-public–private–civil society) collaboration and citizen participation during smart city initiatives [20, 21]. The study is organised as follows: after the introduction, the concepts of the smart city and digital twin are reviewed. The next sections discuss the methodology and results. The results are discussed in the discussion section, and finally, the conclusion section concludes the study.

2 | THE SMART CITY

The concept of a smart city has played a significant role in cities´ digital transformation efforts. The smart city concept has evolved since the 1990s when the cities of Adelaide in Australia and Singapore used the concept of a smart city to describe the future development of the cities. Both cities considered that by reinforcing their broadband network infrastructures, they would be able to accelerate the emergence of digital services and make the cities more attractive for ICT companies to settle in and establish businesses in the city [22, 23].

Global spending on smart city initiatives has steadily increased as cities´ demands for strengthened digital infrastructures and digitised city services continue to grow. It is estimated that the size of the smart city market will double during the next five years [24–26]. Growing smart city markets have been especially attractive for multinational companies (MNCs) operating in the ICT industry. These companies have developed their smart city solutions to close the gap between the demand and supply of digital solutions in smart city markets [27, 28]. However, the dominance of global ICT giants in smart city development has been criticised, and it is argued that MNCs´ sole objective is to drive technology-centric and corporate-driven urban development [27–29]. For this reason, the cities have altered their strategies and are now creating practices that enable more agile quadruple helix collaboration (collaboration with actors, e.g. in academia, from start-ups and citizens), additionally to ICT giants. By strengthening the quadruple helix collaboration, the cities aim to provide equal opportunities for diverse smart city developers and thus reduce the risk of vendor lock-in and the dominance of MSCs in smart city development. Additionally, the quadruple helix model empowers cities to adopt a bottom-up urban development approach which enables integrating citizens as active actors in urban development initiatives [30].

In the European context, a common practice has been to establish technology test and experimentation platforms (TEPs) to support agile smart city development. Smart city TEPs are recognised to offer low-threshold environments in which rapidly evolving digital technologies—such as the IoT, blockchain and AI—can be tested in diverse smart city domains. The smart city TEPs also enable urban developers to evaluate whether the new digital technology or innovation is applicable for broader deployment in different smart city domains [31–33]. Another environment that is popular for testing smart city solutions has been that of living labs, real-world environments for developing and experimenting with smart city services and solutions. Compared to other smart city TEPs, living labs enable integration of final users (citizens) into living lab activities. By integrating real users in the early phase of the digital service development process, smart city developers may receive immediate and more context-specific feedback and evaluate how new digital solutions are adopted and accepted by the citizens and other stakeholders [34–36].

Due to the rapid evolution of digital technologies and services, agile digital technology and service experimentations in smart city TEPs and living lab settings have become well-accepted courses of action in urban development. For example, the city of Helsinki established a separate business unit, Forum Virium Ltd, to support agile smart city development by means of novel digital innovations and technology experimentations [17]. Although the smart city TEP approach has proved to be a viable model for smart city development, it is worth noting that smart city TEP and living lab activities should support overall urban development and be in compliance with city strategies and governance in particular. By integrating smart city TEP activities into comprehensive urban development, the city can deploy the best practices received from technology experimentations to other city domains.

3 | THE DIGITAL TWIN

The digital twin has taken a foothold in product and manufacturing design, but recently, digital twins have also been applied in other industries such as the aerospace, automation, marine, healthcare and energy sectors [13, 14]. The reason for the more widespread utilisation of digital twin technology is that virtual simulation technologies have evolved along with other digital technologies like sensors, the IoT and data analytics [14, 37]. However, the foundation of digital twins lies in static CAD, which enables 3D product design and representation [38]. Whereas CAD is a tool for designing static digital models, digital twin technology provides connectivity between the virtual and physical product. A digital twin is thus a dynamic digital representation of a 3D-designed product or solution which, in the most optimal cases, represents the same features and provides the same information as its physical counterpart [14, 38].

Most commonly, a digital twin is utilised for modelling and simulation, monitoring, verification and control purposes [13, 14], but it is also utilised to calculate and regulate the system status and processes [37]. Furthermore, [14] have classified and divided digital twin applications into the following fields: the modelling of connections, data, interaction and collaboration, and services. As a digital twin is a simulation of a system itself [39], it extends possibilities to model physical and virtual objects and explore, for example, the behaviour of a 3D-designed solution in a virtual space. A digital twin also enables exploration and testing of how physical forces influence a designed object [13, 14, 38]. Using a digital twin for monitoring purposes enables, for example, representation and interpretation of the properties and current state of a physical and virtual object. Novel digital solutions such as the IoT and high-speed connections (including 5G) extend the real-time monitoring and synchronising capabilities of digital twins. The control aspect considers cyber–physical connections, which cover applications where a digital twin directly influences products or manufacturing assets and enables physical objects to be controlled remotely in real time [13, 14, 39].

One very essential part of the digital twin is the connectivity of the virtual and physical counterparts [13]. The ability to model connections and data assists in defining data sources and in determining how data is connected, transmitted, processed and stored in and between the virtual and physical systems [14]. *A one-directional connection* refers to a physical object that only has one-way connectivity to its virtual counterpart [13]. A one-directional data flow and connection is also called *a digital shadow* [37, 40], which considers that 'a change in state of the physical object leads to a change of state in the digital object, but not vice versa' [40]. *A bi-directional connection* refers to a digital twin that forms a mutual connection between the physical and virtual object. Bi-directional connectivity is built on distributed computing devices and data systems that utilise data and real-time connectivity. Bi-directional connectivity enables the digital twin to control its physical counterpart without human intervention [13, 37]. A bi-directional connection consists of different layers (e.g. multiple data sources, physical and virtual devices, sensors, data connection and a cloud-based environment) [41].

3.1 | The benefits of the digital twin

It is argued that a digital twin is a key enabler of digital transformation [40]. Considering the application areas (e.g. product and service design, production, prognostic and health management), organisations may receive multiple benefits from the digital twin technology [14]. Compared with static 3D models, real-time connectivity and data from both virtual and physical objects enable real-time system product design, simulation and testing in less time and with less expenses. It should be noted that a digital twin assists in running many experiments in a virtual environment without having a direct connection with a physical entity. This enables system optimisation and risk elimination (e.g. financial or operational risks). It is furthermore identified that a digital twin minimises design errors, resulting in less failures in a physical system [38, 42]. A digital twin has also proved its efficiency in detecting anomalies and identifying triggering events well before actual failures occur in a cyber–physical system. A digital twin thus extends possibilities to monitor and make predictions about the behaviour and condition of complex physical systems. The predictive quality and analytics of a digital twin contribute to assessment of alternative scenarios and solutions to the probable problems and errors in the cyber–physical system [38, 39, 43].

In the context of the architecture, engineering and construction (AEC) sector, a dynamic digital twin is noted to bridge multi-stakeholder teams and enhance mutual collaboration [44]. Virtual and real-time simulation environments extend the accessibility of diverse stakeholder groups (such as global product designers, research and development teams, final users and customers), so they are able to collaborate jointly on a digital twin platform environment. With digital twin technology, for example, vendors may easily educate and train stakeholders in value networks and provide more extensive customer support for clients [45]. As virtual and physical objects, together with data, form the core of the digital twin [37, 46], a digital twin is a notable technology with which organisations can be assisted in decision-making as well.

4 | METHODOLOGY

This study follows an interpretive research approach with a qualitative exploratory research strategy [47] in order to investigate a relatively new phenomenon: a digital twin´s implementation in smart city settings. Semi-structured interviews (see Table 1) were conducted with urban developers in the city of Helsinki (#1, #2, #3 in the table) and the city of Pietarsaari (#4 in the table). The interviewee in interview #5 represents two organisations: buildingSMART Finland and xD Visuals Ltd. The organisation buildingSMART Finland is part of the international not-for-profit buildingSMART organisation that aims to foster the adoption of building information modelling (BIM) standards and practices as well as the overall digital transformation of the built asset economy ([48]). The interviewee in interview #5 has a role as the head of a city planning industry group of buildingSMART Finland. In the role of CEO, the interviewee in interview #5 represents a company called xD Visuals Ltd, which provides 3D city modelling and digital twin solutions for cities. The interviewees

TABLE 1 Data from interviews and secondary data sources

Interview	Organisation	Data source
#1	Helsinki city	Environmental planner (04/2018)
#2	Helsinki city	Project manager, Helsink i3D+, (09/2020)
#3	Consultant agency, Helsinki smart city development	Consultant, (09/2020)
#4	Pietarsaari city	Assistant-urban planning (06/2021)
#5	BuildingSMART, xD Visuals Oy	Head of city planning & CEO (06/2021)
#6, #7	Platform of trust	CIO (02/2020), CEO (05/2020)
#8	Smart World Pro platform by Cityzenith	Business development manager (02/2020)
	Secondary data:	
#9	Digital twin of Kalasatama district	Kira-digi project report
#10	Open cities planner platform by Agency 9& Bentley	Company website
#11	Platform of trust	Company website, marketing material
#12	Smart World Pro platform by Cityzenith	Company website, marketing material

in interviews #6, #7 and #8 represent companies offering digital twin platforms, technical solutions and a consultancy for smart city developers. Empirical data was enriched with secondary data collected from official project reports, and companies´ websites and marketing material. The data was analysed by following inductive, content analysis techniques. Interviews #2, #3, #4, #5 and #7 were conducted and recorded via online meeting platforms and mobile phone. Recordings were transcribed after the interview sessions. Interviews #1 and #6 were conducted face to face and interview #8 was conducted via an online meeting platform. Data from these interviews were recorded by writing notes. All the interviews (#1–#8) were analysed systematically and in detail afterwards.

5 | RESULTS

The informant in interview #3 emphasised that a city cannot be smart without robust data infrastructure. Robust data infrastructure forms the foundation on which diverse city applications (e.g., in the areas of urban construction and transportation design) can be developed and built. The informant in interview #2 supported this view and expressed that a robust digital city model and data infrastructure enable urban simulations to be set up in an agile and rapid manner. The informant in interview #5 (in the role of CEO) proposed and presented the concept of urban information modelling (UIM) to illustrate a holistic overview of the city. UIM consists of and covers 3D modelling of the whole city, its built environment (such as land, buildings and infrastructure) and also includes geographical information system (GIS) information. UIM forms the foundation for the creation of a city-level digital twin and extends possibilities to simultaneously observe the whole lifecycle of the city: its current city areas, city areas under construction and city areas that are currently being envisaged (the informant in interview #5). The informant in interview #4 pondered about the possibility of creating a holistic city model that would facilitate the city planners´ work and eliminate superfluous work such as accessing the spot physically.

The informants in interviews #2 and 3, however, considered that current 3D data modelling and digital twin technologies serve the city best when the aim is to model a specific city function or use case. As an example, the city may utilise a digital twin to analyse city views, wind conditions, microclimate or traffic and city services. Alternatively, as indicated by the informants in interviews #1 and #2, the city may implement a digital twin to identify and simulate buildings´ energy leakages or to enhance building renovation with a dynamic digital twin. Urban developers may also use a digital twin to anticipate changing climate conditions´ impacts on the built environment by simulating, for example, how rising sea levels or other changes in weather conditions influence a specific urban context and built environment (interview #2 and KIRA-digi project report, 2019). The informant in interview #3 highlighted that prior to launching digital twin initiatives, one important aspect is to define the level of detail (LOD) for the data model. The data model´s LOD determines the extent and relevance of the data and steers developers to make decisions about the extent and relevancy, which improves the design of adequate data models and digital twins.

5.1 | The cityGML standard

The informant in interview #5 (in the role of the head of a city planning industry group) indicated that buildingSMART Finland has formulated and compiled a digital city-planning manual that contains general information of the 3D city modelling practices and standards such as cityGML. The cityGML standard is an open data model and XML-based format is used to store and exchange virtual 3D city models [49]. According to the informant in interview #5, some Finnish cities such as Espoo Turku and Kuopio utilise cityGML through, for example, the Tekla cityGML geographical information system, which enables production of cityGML-based content and data models.

Around six years ago, the city of Helsinki experimented with new digital modelling solutions and applied the cityGML standard in the city´s 3D modelling work. The informant in interview #2 indicated that, as a result of this experimentation project, it was noticed that when compared with static CAD models, the cityGML standard takes 3D urban design and planning to the next level. Ever since the cityGML standard was experimented with by Helsinki urban planners, the standard has been applied in diverse city planning projects in Helsinki.

> *The idea of a digital twin is that you can use it again and again and deliver continued benefits. Data is accumulated and joined [in a digital twin]. The added value of combining data [in a digital twin] is huge. (Informant in interview #2)*

The informant in interview #2 emphasised that with the cityGML standard, urban planners are enabled to enrich digital city models as the standard allows integration of external data sets into the original digital city model. This feature improves the content and visual presentation of the city models and plans. Other benefits that the cityGML offers are that it is an open standard and is available free of charge for users [50]. Consequently, openness and payment-free deployment make the standard affordable for urban developers to deploy in diverse urban development projects. The informant in interview #2 also indicated that, as the cityGML standard is vendor independent, together with the open-data policy of Helsinki, it enables more widespread collaboration with universities and other cities both nationally and internationally (see Figure 1).

One context in which the urban designers of Helsinki implemented the cityGML standard was in the Kalasatama district, a smart city development area in Helsinki. The Kalasatama digital twin initiative was carried out during 2018–2019, and the primary objective of the project was to produce high-quality semantic data models and reality mesh models from the Kalasatama district. These data models, semantic and reality mesh models, constituted a platform for the existing and new digital urban experimentation projects that are carried out in the Kalasatama district. During the Kalasatama digital twin project, a specific application called Open Cities Planner was developed to complement and reinforce the usage of the Kalasatama digital twin platform. The purpose of Open Cities Planner was to connect data and create visual use cases, which can be experimented with in the virtual Kalasatama environment later on, before final execution. The Open Cities Planner platform also extended possibilities to improve citizen participation and interaction among Kalasatama residents. As an example, one use case—the public participation GIS (PPGIS)

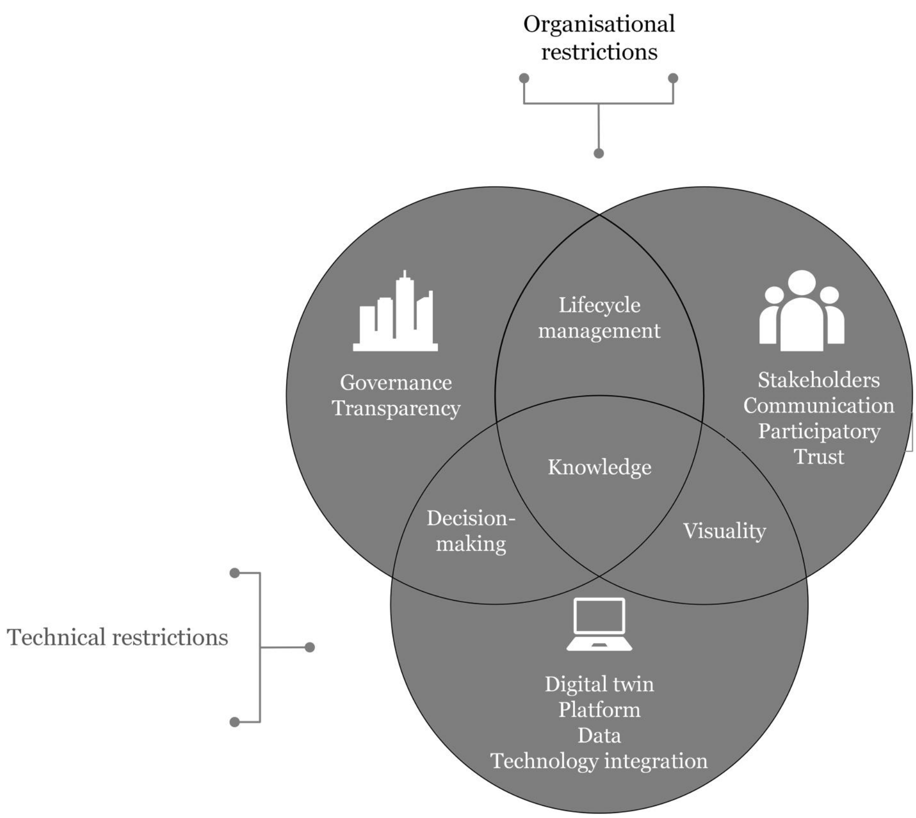

FIGURE 1 A digital twin´s implications in the smart city context

poll—was carried on the Open Cities Planner platform to investigate Kalasatama residents´ preferences for locations that they would recommend for people visiting Kalasatama. Kalasatama semantic and reality mesh models were also used for wind and solar simulation purposes. The aim of the wind and solar simulations was to demonstrate airflows and examine the shadows cast over the Kalasatama district. Further, the simulations enabled analysis of solar rays´ and air pressure´s impacts on the built environment in Kalasatama [51].

5.2 | Interaction with smart city interest groups

Even though a dynamic digital twin is still a niche technology in the smart city context, experiences from digital twin´s practical implementation in Helsinki reinforce the impression that a digital twin is a valid technology in diverse urban planning and development domains. As identified by the informants in interviews #2 and #3, the digital twin appears to be beneficial, especially in the early phase of urban planning, as the virtual replica enables exploration of a specific city function or use case and evaluation of alternative solutions in the virtual environment before final implementation. From the cognitive perspective, the informant in interview #2 emphasised that the greatest advantage of creating 3D city models is that they increase the general understanding and awareness of urban development initiatives:

> *If you make an analysis, you are able to visualise and illustrate things and build up certain services so that one can understand big and small issues and their relations and connections. (Informant in interview #2)*

Other informants (in interviews #1, #3, #4, and #5) supported this view by stressing that 3D city models and digital twin technology assist urban developers in objectifying and forming a shared vision and understanding of the city design subject matter. The informant in interview #4 highlighted that it is easier to illustrate land use and zoning plans for decision makers when the plans are in a visual 3D format instead of a 2D format. As an example, the decision makers get a better understanding of the size of the buildings that can be constructed on the building site (according to the informant in interview #4).

Another perspective the interviewees addressed was that the 3D city modelling enables enrichment of digital city models with external data and presentation of more knowledge-based city scenarios (according to, e.g. the interviewee in interview #2). Consequently, more informative and realistic city scenarios enable elimination of emotional statements and opinions during the decision-making process. The informant in interview #3 expressed the following:

> *As an example, the large-scale urban development case X contains multiple decision-making points. For the members of the local urban planning committee, who are mostly laypeople, this is a highly visual presentation of the subject matter on which they should make a decision during the meeting. [For them it is easier] to evaluate whether we should vote for this city plan/scenario or another. And if it is possible to enter financial information, timetables and environmental implications [into 3D city model], then that is better. (Informant in interview #3)*

Similarly, the informants in interviews #2 and #5 highlighted that up-to-date 3D city models assist decision makers (e.g., the members of local urban planning committees) to base their decisions on actual data instead of on feelings and emotions. The informant in interview #2 disclosed that

> *With visual analysis, we are able to illustrate how [different alternatives and scenarios] influence real views, wind, microclimate, services, traffic etc. We are able to depict the case in more detail and avoid emotional assessments.*

Indeed, an urban digital twin is a platform and common approach that can be used to find the best practices in order to solve trivial and non-trivial urban challenges. The study informants in interviews #1, #2, #3, #4 and #5 highlighted that urban digital twins facilitate the governance and management of smart city initiatives and consolidate trustful and transparent interaction with partners such as civil engineers, architects and building owners or, alternatively, with third parties such as citizens, as we have learnt from the case of the Kalasatama digital twin project. The informant in interview #2 expressed that in a future dynamic, digital twins could also be formed of intangible social networks that are additional to tangible physical objects and assets.

5.3 | The limiting factors of a digital twin

Notwithstanding that a digital twin has potential in urban design, the organisational and technical issues appear to hinder the technology´s extensive deployment in smart city development (see Figure 1). For instance, in organisational settings, the informant in interview #3 expressed that certain city authority processes, such as an application process for building permits, do not fully support data generation and sharing in digital formats. Alternatively, the city organisation does not see that the novel digital technologies create any concrete added value for existing business procedures, and for this reason, the organisation does not invest in technical and human resources. The informant in interview #5 underlined that, technically, things are available and working with the digital twin, but the greatest challenge and obstacle result from the people themselves: the challenge is how willing the people working in the city organisations are to change their thoughts, attitudes and courses of action. Changes in organisational culture and city processes are thus essential if the city aims to exploit data modelling and digital twin technologies to a greater extent. However, the changes in organisational culture and processes should also concern the actors in the entire value network of urban development. A shared agreement with actors to implement data modelling in urban development projects fosters the adoption and diffusion of data modelling and digital twin techniques (including the cityGML standard), but more importantly, a joint agreement enables the actors to exploit the advantages that a dynamic digital twin engenders for all the actors in the entire value network.

Other identified restrictions that hinder a digital twin´s exploitation in urban planning concern, for example, the number and size of data files, data integration and computing power. The informant in interview #1 highlighted that acquiring the correct data and retrieving and modifying data sets for the purposes of 3D models can be challenging. The informant in interview #1 also expressed that generating high-quality 3D models can be laborious as the data used for 3D models may need manual cleaning and preparation (cf. [18]). In the case of the Kalasatama digital twin project, it was identified that integration of a large amount of data from different databases into the visual 3D model set high demands for computing power. Generating a 3D mesh model required high computing capacity as the 3D mesh model contained a large amount of data from aerial photos, point cloud datasets and laser scanning. The 3D mesh model was finally created by the ContextCapture application [51].

Contrary to the understanding of the informants in interviews #2 and #3 regarding scaling digital twin technology to concern the entire city, the informant in interview #5 stressed that, along with new technologies, it is possible to generate a realistic digital twin of the entire city. In an authentic virtual city environment, the designers may integrate, e.g., planned construction work into a realistic virtual city environment and evaluate the heights and foundations of the streets and buildings in a specific city district or block (see Figure 2).

The informant in interview #5 also expressed that it is currently even feasible to process large data sets with mobile phones:

> *I can open large-scale infrastructure projects with my mobile phone in seconds when I am visiting and working in a terrain. (Informant in interview #5)*

It appears that along with the rapid evolvement of digital twins´ technical capabilities, to an increasing extent, urban designers have more sophisticated tools and solutions available with which connectivity between the virtual and physical city can be built.

6 | DISCUSSION

City organisations are complex socio–technical systems. The concept of the smart city has been applied to solve the non-trivial challenges that urbanisation and climate change have

FIGURE 2 An illustrative drawing of a building project (© [52])

engendered for cities. However, rapidly evolving digital technologies set challenges for cities adopting and integrating novel digital technologies into the city processes and activities and creating additional value for the city (cf. [53, 54]). This study contributes to the discussion of smart city development with digital technologies and considers digital twin technology´s applicability in urban planning and development initiatives. The study took place in a setting where the deployment and adoption of digital twin technology is in its early phase (cf. the diffusion of innovation [55]). Data for this study was primarily collected by interviewing smart city practitioners. The data included and comprised exploratory interviews with city representatives (urban planning, $n = 3$), consultants and digital twin platform providers ($n = 5$). Research data was complemented with secondary data such as project reports and websites. Combining the range of qualitative methods (interviews, project reports and websites) provided access to divergent information on the study phenomenon and helped analyse the findings.

Agile digital technology and service experimentation practices have become well-accepted courses of action in urban development (cf., e.g. [31, 34, 36]). As an example, the city of Helsinki has actively invested in smart city pilots and developed a culture for agile and low-threshold technology experimentation practices. With agile technology pilots, the city aims to motivate and mobilise smart city practitioners to develop concrete smart city solutions, which can later be drawn on in city-level strategic projects [17]. As part of technology experimentations, the urban designers in Helsinki city experimented with the cityGML standard, a standard for creating virtual 3D models. The positive outcome of the cityGML experimentation encouraged the urban designers to implement the standard in other smart city initiatives, leading to the application of cityGML as part of regular urban design procedures in Helsinki. Experimentation with novel digital technology, in this case the cityGML, enabled urban designers to evaluate a new 3D modelling standard in a realistic urban design environment and to gain knowledge about the solution itself (cf. [33]) and its applicability in urban design activities. Accordingly, the results of the cityGML experimentation provided a basis for Helsinki urban designers to investigate digital twin solutions (including the cityGML standard and, later, other digital 3D modelling platforms and game engine technologies) on a broader scale in Helsinki and afterwards apply the concept to create a virtual replica of a specific city district, function or use case. Helsinki has been a pioneer city in exploiting cityGML in urban development initiatives. Other cities in Finland have benefitted from cityGML indirectly through the Tekla software.

Another important element of the smart city and digital twin concepts concerns data. The study informants emphasised that a solid data infrastructure forms the foundation for smart city digital twins and applications. According to findings in reference industries (cf., e.g. [14, 44]), integration of city data, such as energy consumption or traffic data, into digital city models enriches the content of urban digital twins. As in the case of Kalasatama, the data-enriched digital twins were employed to simulate the impacts of changes associated with natural phenomena and weather conditions on the built environment. Moreover, the urban developers in Helsinki utilised other dynamic 3D city models (e.g., the Energy Atlas platform) to simulate energy information, such as information on the energy leakages of buildings, and to educate property owners and citizens about more energy-efficient consumption and carbon neutral behaviour (cf. [18]).

To an increasing extent, learning and knowledge aspects are underlined in the contexts of a digital twin and smart city. The concept of a cognitive city is introduced to describe the socio–technical aspect and thus the interplay of humans and technology in smart city initiatives. A cognitive city recognises individuals and technical solutions as sources of information and knowledge, which augment cities´ possibilities to learn and adapt to changes that occur in the city environment [19, 56]. In the case of Helsinki, the urban designers have, as a result of exploiting digital twins in urban planning, been able to intensify the number of smart city experimentations and present more realistic city scenarios that draw on concrete, actual data. By doing so, the urban developers have eliminated the statements that are built on emotions and assumptions during the decision-making process.

Evidently, digital twins are low-threshold platforms that hasten knowledge sharing and learning with smart city practitioners and consolidate collaborations with diverse stakeholders such as urban designers, civil engineers, constructors, city authorities (including local politicians) and citizens. As presented by the interviewees, urban design with digital twins has improved stakeholder communication, which has made city development and design processes more transparent and open. Digital twin platforms were also exploited to integrate citizens into urban development initiatives and activities in Helsinki (cf. [3]). In Helsinki, dynamic 3D city models have improved the governance of diverse urban planning projects and the management of the practical implementation of urban development initiatives (smart city governance; see, e.g. [17, 30]). Digital twins have also served the city of Helsinki in helping to observe the lifecycle of certain districts and gain more context-specific information on the city entities and conditions.

Despite the promising features that the dynamic digital twin currently offers to smart city practitioners, some organisational and technical restrictions prevent the full exploitation of dynamic digital twins in urban settings. Regarding the quadruple helix collaboration and organisational challenges in particular, cities need to consider the current organisational culture and evaluate if changes needs to be made (e.g., in city processes, structures and practices) so that the benefits of the dynamic digital twin can be achieved in the future work of urban development. Furthermore, city employees´ attitudes, skills and courses of action influence how effectively digital twin technology is adopted and deployed in the city organisation. In this regard, the research of an organisation´s digital transformation (e.g. [57, 58]) and theories of innovation diffusion and socio–technical perspectives (e.g. [55, 59]) would shed more light on and improve knowledge on this matter.

Considering technical restrictions (e.g., restrictions related to computing power, data quality and processing; cf. [18]), the study results indicate that advancements in digital technologies make the production of digital twins from the entire city easier, faster and more cost-effective. Sophisticated cyber–physical systems augment a digital twin´s deployment from single physical use cases (e.g., the design of buildings and infrastructure) to also concern digital twin deployment in other city domains, such as 3D modelling of the processes and functions of healthcare, education and social services.

7 | CONCLUSION

The digital twin is an emerging technology in smart city research and discussion. In the light of the study interviews, solid data infrastructure constitutes the basis for creating digital twin platforms on which smart city practitioners may develop, for example, digital city services and applications, carry out smart city simulations and demonstrate alternative urban development scenarios for city stakeholders including politicians, decision makers and citizens. The practical implementation of 3D city modelling discloses that concrete and realistic urban development simulations have improved the quality of public debate and strengthened learning and knowledge-based decision-making with heterogeneous urban stakeholders. Developing a culture for agile technology experimentation has, in turn, motivated and fostered smart city practitioners to adopt 3D city modelling solutions such as the cityGML standard and dynamic digital twins in urban planning. The deployment of digital twin technology has also advanced citizen inclusion and overall transparency and trust among actors participating in smart city initiatives. These factors, together with the concept of UIM presented in the study, have the potential to strengthen the digital transformation of cities and thus smart city development as well as the governance and management of the smart city.

Regardless of the benefits of a digital twin, some restrictions hinder the deployment of a digital twin in urban settings. Generating high-quality digital twins is laborious as data cleaning and preparation needs manual work. Dynamic digital twins also require high computing and data processing power. However, recent technology development has accelerated the generation of city-level digital twins, making city models with digital twins more affordable and easier for cities. Considering the adoption and diffusion of digital twins in smart city development, cities need to consider changes in organisational culture, processes and structures to guarantee fluent digital data flow between the cities' information systems and entities. To overcome the obstacles, the cities need to consider a strategic-level approach and commitment in an effort to integrate the use of a digital twin as part of regular urban design practices. Investments (financial and educational), both in human and technical capabilities, assist cities in this endeavour.

Due to the early stage of digital twins' diffusion in smart city settings, this study covers a relatively limited number of practical digital-twin experiences in a smart city setting. Additionally, the empirical data mainly concerns one city. However, the study results give evidence that digital twin technology in a smart city setting is an appropriate solution. Application of a digital twin in smart city research would allow for development and analysis, for example, social networks, social inclusion and citizen interaction, which would benefit a bottom-up urban development approach. Alternatively, considering cities' urban metabolism and carbon neutrality objectives, the concept of digital twin technology could assist the city in exploring urban metabolism and sustainability aspects and in developing new innovate solutions (e.g., in the area of the circular economy).

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CONFLICT OF INTEREST

None.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

In Figure 2 picture is copyright picture from xD Visuals Ltd. I have permission to use the picture in this research study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. Carvalho, L.: Smart cities from scratch? A socio-technical perspective. Camb. J. Reg Econ. Soc. 8(1), 43–60 (2014)
2. Gabrys, J.: Programming environments: environmentality and citizen sensing in the smart city. Environ. Plann. Soc. Space. 32(1), 30–48 (2014)
3. Lea, R., Blackstock, M., Giang, N., Vogt, D.: Smart cities: engaging users and developers to foster innovation ecosystems. In: Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers, pp. 1535–1542 (2015)
4. Olivares, T., Royo, F., Ortiz, A.M.: An experimental testbed for smart cities applications. In: Proceedings of the 11th ACM International Symposium on Mobility Management and Wireless Access, pp. 115–118. (2013)
5. Sánchez, L., Gutiérrez, V., Galache, J.A., Sotres, P., Santana, J.R., Casanueva, J., Muñoz, L.: SmartSantander: experimentation and service provision in the smart city. In: International Symposium on Wireless Personal Multimedia Communications (WPMC), pp. 1–6. (2013)
6. Zanella, A., Bui, N., Castellani, A., Vangelista, L., Zorzi, M.: Internet of things for smart cities. IEEE InternetThings J. 1(1), 22–32 (2014)
7. Swilling, M., Robinson, B., Marvin, S., Hodson, M.: City-Level Decoupling: Urban resource flows and the governance of infrastructure transitions. Summary for policy makers. Chapter: Introduction and overview. UNEP (2013)
8. Bahers, J.B., Barles, S., Durand, M.: Urban metabolism of intermediate cities: the material flow analysis, Hinterlands and the Logistics-Hub function of Rennes and Le Mans (France). J. Ind. Ecol. 23(3), 686–698 (2019)
9. Gandy, M.: Rethinking urban metabolism: water, space and the modern city. City. 8(3), 363–379 (2004)
10. Kennedy, C., Pincetl, S., Bunje, P.: The study of urban metabolism and its applications to urban planning and design. Environ. Pollut. 159(8-9), 1965–1973 (2011)
11. Shiode, N.: 3D urban models: recent developments in the digital modelling of urban environments in three-dimensions. GeoJournal. 52(3), 263–269 (2000)
12. Trubka, R., Glackin, S., Lade, O., Pettit, C.: A web-based 3D visualisation and assessment system for urban precinct scenario modelling. ISPRS J. Photogrammetry Remote Sens. 117, 175–186 (2016)
13. Enders, M.R., Hoßbach, N.: Dimensions of Digital Twin Applications-A Literature Review. 25th Americas Conference on Information Systems, AMCIS 2019 (2019)
14. Tao, F., Zhang, H., Liu, A., Nee, A.Y.: Digital twin in industry: state-of-the-art. IEEE Trans. Indus. Inform. 15(4), 2405–2415 (2019)
15. Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., Yamu, C.: Urban digital twins for smart cities and citizens: the case study of Herrenberg, Germany. Sustainability. 12(6), 2307 (2020)
16. Dignan, J.: Smart cities in the time of climate change and Covid-19 need digital twins. IET Smart Cities. 2(3), 109–110 (2020)
17. Hämäläinen, M.: A framework for a smart city design: digital transformation in the Helsinki smart city. In: Entrepreneurship and the Community, pp. 63–86. Springer, Cham (2020)
18. Ruohomäki, T., Airaksinen, E., Huuska, P., Kesäniemi, O., Martikka, M., Suomisto, J.: Smart city platform enabling digital twin. In: 2018 International Conference on Intelligent Systems (IS), pp. 155–161. IEEE (2018)
19. Finger, M., Portmann, E.: What are cognitive cities? In: Towards Cognitive Cities, pp. 1–11. Springer, Cham (2016)
20. Baccarne, B., Schuurman, D., Mechant, P., De Marez, L.: The role of urban living labs in a smart city. In: XXV ISPIM Innovation Conference (2014)
21. Borkowska, K., Osborne, M.: Locating the fourth helix: rethinking the role of civil society in developing smart learning cities. Int. Rev. Educ. 64(3), 355–372 (2018)
22. Shetty, V.: A tale of smart cities. Commun. Int. 24(8), 16–18 (1997)
23. Tokmakoff, A., Billington, J.: Consumer services in smart city Adelaide. In: Paper published at HOIT 94. Proceedings of an International Cross-disciplinary Conference on Home-Oriented Informatics, Telematics & Automation. University of Copenhagen (1994)
24. IDC International Data Corporation: Worldwide Smart Cities Spending Guide (2020). Ref. 20.11.2020. https://www.idc.com/getdoc.jsp?containerId=IDC_P37477
25. Research and Markets (2020). Ref. 18.11.2020. https://www.researchandmarkets.com/reports/5146372/global-smart-cities-market-

by-smart?utm_source=CI&utm_medium=PressRelease&utm_code=bf92ng&utm_campaign=1447907+-+Global+Smart+Cities+Market+to+2025%3a+Increasing+Number+of+Government+Initiatives+and+PPP+Models+for+Smart+Cities&utm_exec=chdo54prd
26. Statista: Spending on smart city projects from 2019 to 2025 (2020). Ref. 18.11.2020. https://www.statista.com/statistics/1111626/worldwide-smart-city-market-revenue/
27. Söderström, O., Paasche, T., Klauser, F.: Smart cities as corporate storytelling. City. 18(3), 307–320 (2014)
28. Vilajosana, I., Llosa, J., Martinez, B., Domingo-Prieto, M., Angles, A., Vilajosana, X.: Bootstrapping smart cities through a self-sustainable model based on big data flows. IEEE Commun. Mag. 51(6), 128–134 (2013)
29. Albino, V., Berardi, U., Dangelico, R.M.: Smart cities: definitions, dimensions, performance, and initiatives. J. Urban Technol. 22(1), 3–21 (2015)
30. Hämäläinen, M., Tyrväinen, P.: Improving smart city design: a conceptual model for governing complex smart city ecosystems. In: Bled eConference. University of Maribor Press (2018)
31. Hamalainen, M., Tyrvainen, P.: A framework for iot service experiment platforms in smart-city environments. In: 2016 IEEE International Smart Cities Conference (ISC2), pp. 1–8. IEEE (2016)
32. Ibba, S., Pinna, A., Seu, M., Pani, F.E.: CitySense: blockchain-oriented smart cities. In: Proceedings of the XP2017 Scientific Workshops, pp. 1–5. (2017, May)
33. Sanchez, L., Muñoz, L., Galache, J.A., Sotres, P., Santana, J.R., Gutierrez, V., Ramdhany, R., Gluhak, A., Krco, S., Theodoridis, E., Pfisterer, D.: SmartSantander: IoT experimentation over a smart city testbed. Comput. Network. 61, 217–238 (2014)
34. Ballon, P., Pierson, J., Delaere, S.: Test and experimentation platforms for broadband innovation: Examining European practice. Available at SSRN. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1331557 (2005)
35. Benabbas, A., Elmamooz, G., Lagesse, B., Nicklas, D., Schmid, U.: Living Lab Bamberg: an infrastructure to explore smart city research challenges in the wild. KI-Künstl. Intell. 31(3), 265–271 (2017)
36. Schaffers, H., Sällström, A., Pallot, M., Hernández-Muñoz, J.M., Santoro, R., Trousse, B.: Integrating living labs with future internet experimental platforms for co-creating services within Smart Cities. In: International Conference on Concurrent Enterprising: 20/06/2011-22/06/2011. IEEE Communications Society (2011)
37. Zheng, Y., Yang, S., Cheng, H.: An application framework of digital twin and its case study. J. Ambient Intell. Humaniz. Comput. 10(3), 1141–1153 (2019)
38. Grieves, M., Vickers, J.: Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. In: Transdisciplinary Perspectives on Complex Systems, pp. 85–113. Springer, Cham (2017)
39. Negri, E., Fumagalli, L., Macchi, M.: A review of the roles of digital twin in cps-based production systems. Procedia Manuf. 11, 939–948 (2017)
40. Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W.: Digital twin in manufacturing: a categorical literature review and classification. IFAC-PapersOnLine. 51(11), 1016–1022 (2018)
41. Redelinghuys, A.J.H., Kruger, K., Basson, A.: A six-layer architecture for digital twins with aggregation. In: International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing, pp. 171–182. Springer, Cham (2019)
42. Vachálek, J., Bartalský, L., Rovný, O., Šišmišová, D., Morháč, M., Lokšík, M.: The digital twin of an industrial production line within the industry 4.0 concept. In: 2017 21st International Conference on Process Control (PC), pp. 258–262. IEEE (2017)
43. Ding, K., Chan, F.T., Zhang, X., Zhou, G., Zhang, F.: Defining a digital twin-based cyber-physical production system for autonomous manufacturing in smart shop floors. Int. J. Prod. Res. 57(20), 6315–6334 (2019)
44. Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., Holmström, J.: Digital twin: vision, benefits, boundaries, and creation for buildings. In: Abbott, D. (ed.) IEEE Access, vol. 7, pp. 147406–147419. (2019). https://doi.org/10.1109/ACCESS.2019.2946515
45. Alaei, N., Rouvinen, A., Mikkola, A., Nikkilä, R.: Product processes based on digital twin. In: Commercial Vehicle Technology 2018, pp. 187–194. Springer Vieweg, Wiesbaden (2018)
46. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F.: a. Digital twin-driven product design, manufacturing and service with big data. Int. J. Adv. Manuf. Technol. 94(9-12), 3563–3576 (2018)
47. Creswell, J.W., Poth, C.N.: Qualitative inquiry and research design: Choosing among five approaches. Sage publications (2016)
48. buildingSMART international. https://buildingsmart-1xbd3ajdayi.netdna-ssl.com/wp-content/uploads/2019/05/buildingSMART_A5-FLYER_V5-1.pdf (2021)
49. Open Geospatial Consortium. https://www.ogc.org/standards/citygml (2021). Retrieved June, 14
50. Erving, A.: Paikkatiedoista kaupunkimalleihin: CityGML selvitystyö. Teknillinen korkeakoulu, fotogrammetrian ja kaukokartoituksen laboratorio. Espoo (2008)
51. Kira-digi: Kalasataman digitaaliset kaksoset. Kira-digi-kokeiluhankkeen loppuraportti. Final report of Kira-dig project (2019). Ref. 03.02.2020. https://www.hel.fi/static/liitteet-2019/Kaupunginkanslia/Helsinki3D_Kalasatama_Digital_Twins.pdf
52. XD Visuals Ltd: An illustrative drawing of a building project. [Photograph] (2021)
53. Abella, A., Ortiz-de-Urbina-Criado, M., De-Pablos-Heredero, C.: A model for the analysis of data-driven innovation and value generation in smart cities' ecosystems. Cities. 64, 47–53 (2017)
54. Fernandez-Anez, V., Fernández-Güell, J.M., Giffinger, R.: Smart City implementation and discourses: an integrated conceptual model. The case of Vienna. Cities. 78, 4–16 (2018)
55. Rogers, E.M.: Diffusion of preventive innovations. Addict. Behav. 27(6), 989–993 (2002)
56. Moyser, R., Uffer, S.: From smart to cognitive: a roadmap for the adoption of technology in cities. In: Towards Cognitive Cities, pp. 13–35. Springer, Cham (2016)
57. Chanias, S., Hess, T.: Understanding digital transformation strategy formation: insights from Europe's Automotive Industry. In: PACIS, pp. 296 (2016)
58. Singh, A., Hess, T.: How chief digital officers promote the digital transformation of their companies. MIS Q. Exec. 16(1), 1–17 (2017)
59. Bostrom, R., Heinen, J.: MIS problems and failures: a socio-technical perspective part II: the application of socio-technical theory. MIS Q. 1, 11–28 (1977)

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