City Digital Twins for Urban Resilience

Research Orientation Report
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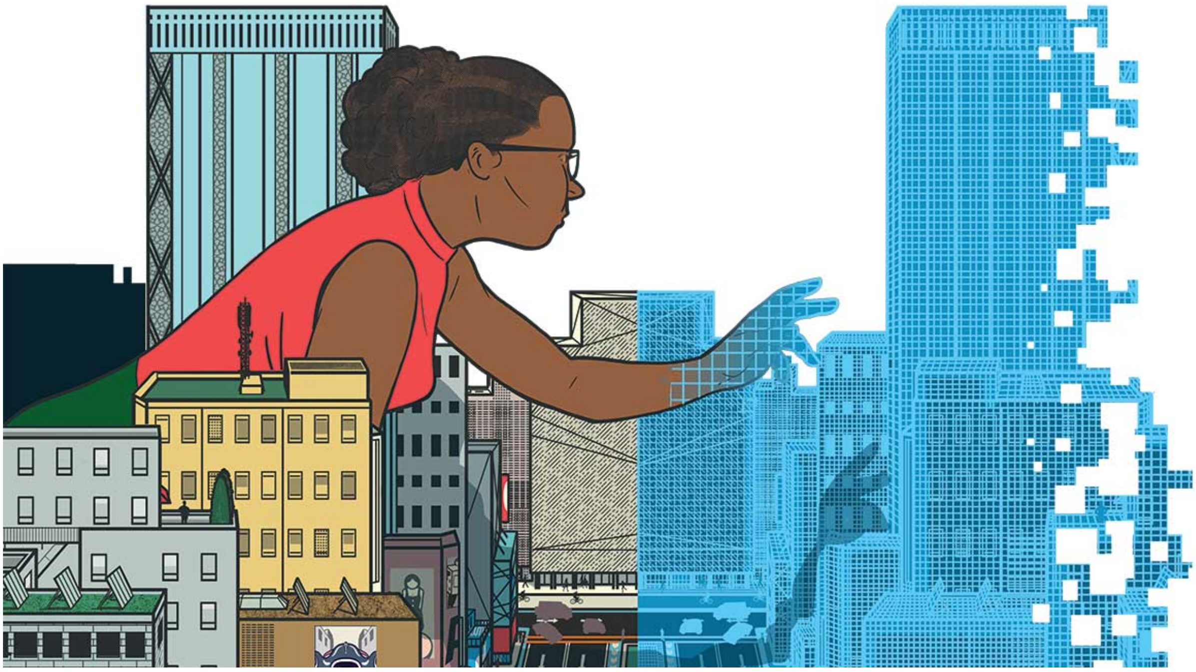

Illustration by Jason Schneider (Hurtado & Gomex, 2021)

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- **Laura Mrosla**: PhD Student at Aalto University, Finland and Tallinn University of Technology, Estonia, Affiliated Researcher at FinEst Center for Smart Cities (Green Infrastructure in Urban Digital Twins / Smart Cities)
- **Katia Tynan**: Manager of Resilience and Disaster Risk Reduction at the City of Vancouver
- **Mingyu Zhu**: PhD Student at Newcastle University (Urban digital twins) in collaboration with Defense Science and Technology Laboratory

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Introduction

With increased urbanization and the impacts of climate change, cities around the globe are developing tools and methods to build their resilience towards acute challenges and longer term changes such as extreme heat, severe storms, earthquakes, and other acute and chronic hazards (Resilient Cities Network, n.d.). Simultaneously, advances in Internet of Things (IoT) technology, the development of computational power and expanding 3D modelling abilities have enabled a growing interest in the potential for the digital twin of cities to address pressing challenges in data-driven, efficient and proactive ways (Deng, Zhange & Shen, 2021).

In 2004, a high intensity typhoon impacted the Japanese city of Takamatsu during high-tide hours. This event led to severe flooding, the damage of 15,000 buildings and the loss of two people's lives (Fiware Foundation, 2020). According to the Fiware Foundation report (2020), since the disaster occured, Takamatsu City has developed a comprehensive visualization and prediction system to inform its disaster management practices and enable proactive interventions such as preemptive evacuation of vulnerable areas. As shown in Figure 1, the platform draws sensor data that tracks water levels, tide levels, shelter availability, and traffic behaviour as well as rainfall forecasts to inform real-time decision-making and mitigate the impacts of future natural hazards.

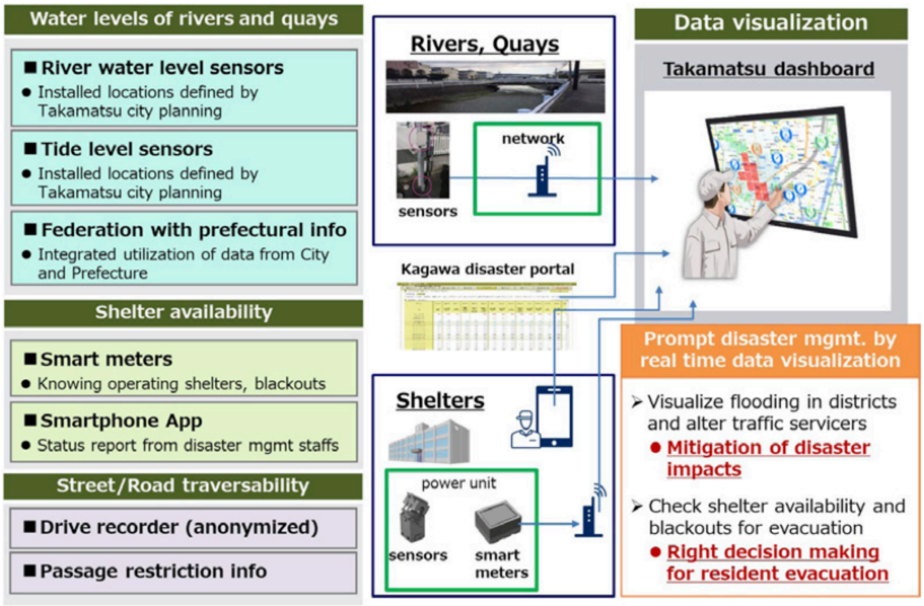

Figure 1. Takamatsu City's Disaster Management Solution
(Fiware Foundation, 2020, p. 4)

This digital representation of Takamatsu, which models local phenomena based on real-time data and helps inform decision making, can be considered the digital twin of the city. By highlighting some key trends and questions at the intersection of resilience and digital twins, this paper examines the question: how might City Digital Twins (CDTs) support the development of more resilient urban communities? In section 1, the methodology is described, followed by a discussion of the "City Digital Twin" definition in section 2. Key findings related to the various ways in which CDTs may be relevant to resilience planning are outlined in section 3. Section 4 focuses on findings relating to the technical requirements, benefits and challenges of CDT implementation.

1. Methodology

The research informing this paper primarily involved a literature review to identify key trends and emerging questions at the intersection of the urban planning concepts of “resilience” and “City Digital Twin.” To carry out this review, a list of relevant concepts was developed (e.g. Resilience, Digital Twin*, Urban Planning, Hazard*) and used to write search queries adapted to two specific platforms: Scopus and Web of Science. See Appendix A for the specific key terms and search queries. The initial systematic searches were restricted to the last five years and were filtered to academic articles only. From this initial list of literature, additional sources were identified based on the reference list from each article in a snowball fashion. A summary table of the City Digital Twins considered in this report can be found in Appendix C.

In addition to the literature review, the research also involved semi-structured expert interviews with four researchers and practitioners in the field(s) of resilience and/or CDTs. These experts were self-selected (through an open call on LinkedIn) and one was directly invited via email due to previous professional interactions. The purpose of these conversations was to enrich the research with practical insights and experiences that may not be readily available in written or digital form. These interviews also informed some of the literature reviewed in this paper. Guiding questions were prepared and shared with interviewees prior to each meeting, and the interviews were flexible to accommodate for a variety of knowledge and experiences related to the topic. Ideas and anecdotes informed by the interviews have been cited as “personal communication.”

2. What is a City Digital Twin?

Definitions of “a city’s digital twin” are as diverse as the digital twins themselves. In academia and industry, a variety of terms are used to refer to this concept, including “Digital Twin” (Schrotter & Hürzeler, 2020), “Urban Digital Twin” (Dembski, Wössner, Letzgus, Ruddat & Yamu, 2020), “Local Digital Twin” (Kogut, 2021) and “City Digital Twin” (Shahat, Hyun & Yeom, 2021), which is the term used throughout this paper. The concept originates from the manufacturing industry: a digital twin is the digital representation of an item that enables designers to test a product in various computer-modelled environments in order to simulate the object’s physical responses to external conditions and improve the design prior to building physical prototypes (Deng et al., 2021).

Applied to cities, the term is used to refer to models varying in complexity, purpose and levels of interaction with the physical world (R. Herzog, personal communication, 9 August, 2022). The excitement around its potential has led to it becoming a kind of “buzz word” with many interpretations (L. Mrosla, personal communication, 17 August, 2022). Many publicly accessible so-called “Digital Twins” are simply 3D models. According to Shahat et al. (2021), the difference between the two concepts is that a 3D model is often a “digital visualisation” of an urban object system that can be used for analysis and decision-making, whereas a City Digital Twin (CDT) implies some kind of “interaction between physical reality and [the] virtual model” (p. 3). They explain that the interaction involves a flow of data between the city and its twin, which is made possible by the increasing collection and accessibility of data from Smart City technology. With the help of real-time and dynamic information, changes in the physical world are depicted in the CDT; figure 2 illustrates the level of precision depicted in the Virtual Singapore CDT.

Block 179 Bishan Street 13
Ventilation: **shaded windows**
Exposure to direct sunlight:
4 hr per day
Window ledge material:
concrete

Figure 2. Virtual Singapore CDT (video screenshot)
(National Research Foundation, n.d.)

In order to reflect urban systems with some kind of accuracy, a CDT can be conceptualized as “a system of interconnected digital twins” of different urban systems (Ivanov, Nikolskaya, Radchenko, Sokolinsky & Zymbler, 2020, p. 179) that are informed by real-time data collected from various sources. Each digital twin models a specific urban component, such as “buildings, traffic, air conditioning, [or] microclimate” (Aydt, 2020, p. 9). The CDT acts as a container and connector for these different digital twins, aiming to model the urban environment as a whole (Dembski, Wössner & Yamu, 2019, p. 2). In some cases, a CDT may simulate only a portion of an urban region that is particularly complex to manage, economically significant and/or vulnerable to hazards, such as a transportation hub. One such example is the Port of Tyne, which is the test ground for Mingyu Zhu, who is pursuing his PhD on digital twin concepts for understanding urban dynamics and real-time situational awareness (personal communication, August 10, 2022).

CDTs have a vast range of potential uses, as shown in figure 3. Beyond focusing on visualizations, many definitions of the CDT emphasize their role in “present[ing] current and forecast[ing] future conditions in ways that improve decision-making” (Ford & Wolf, 2020, p.4). Park & Yang assert that “the virtual environment must have a sophisticated mechanism to plan, simulate, assess, and monitor the physical world” (2020, p. 4) and Aydt (2020) emphasizes that they “can be used to conduct what-if analyses and perform experiments with a city in-silico that would otherwise not be possible in the real world” (p. 9).

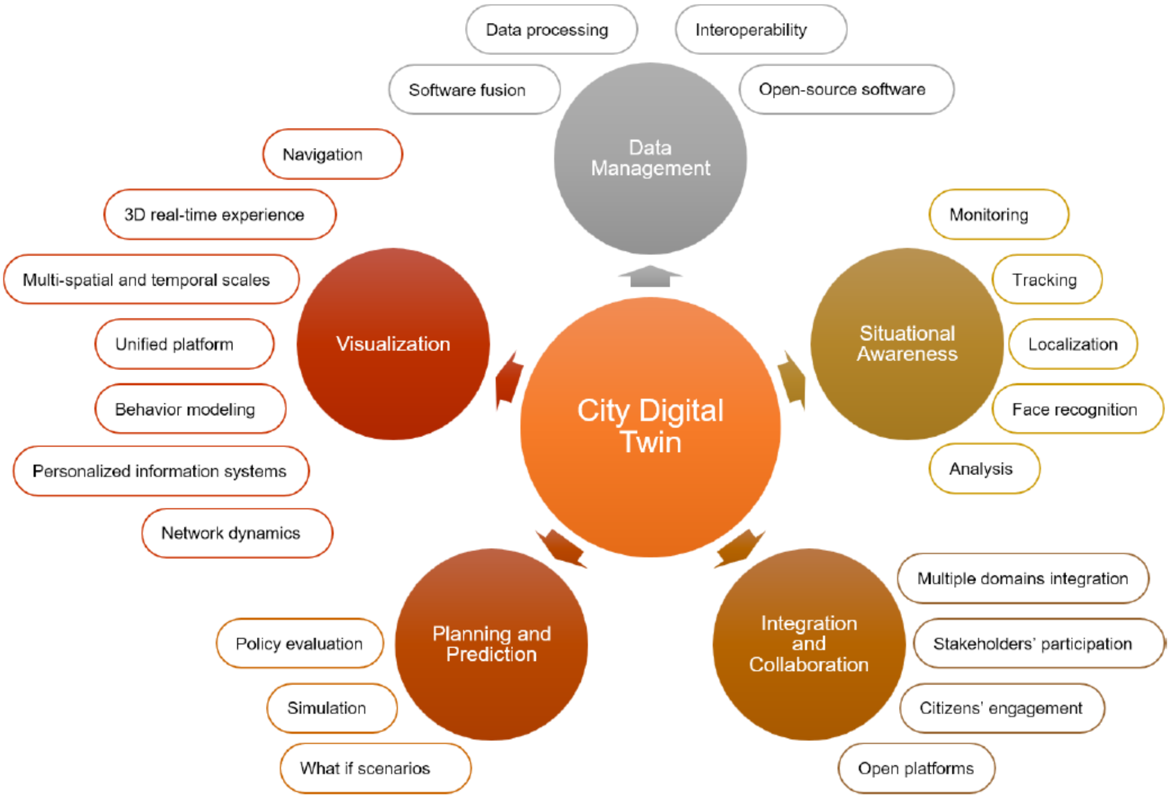

Figure 3. City Digital Twin potentials
(Shahat et al., 2021, p. 13)

Some academics take this one step further, stating that a true City Digital Twin must also involve the digital realm exerting influence on the physical world, such as through automated data-driven responses to situations (Shahat et al., 2021). Based on this definition, no true fully integrated CDT exists, and some experts in the field explain that the current platforms should rather be referred to as “Digital Shadows.” In the case of the Port of Tyne CDT research, the eventual goal is to have the digital twin be one step ahead of reality, as opposed to a “copy-paste” version of the real world (M. Zhu, personal communication, August 10, 2022). Considering that this implementation of the CDT is not quite within reach, the following definition is used in this paper: a City Digital Twin is the multi-layered digital representation of a city that enables the visualization, simulation and evaluation of urban interventions based on dynamic data about the physical and social systems that are embedded in the city itself.

3. Tackling Urban Resilience with CDTs

The concept of “resilience” is also one with many interpretations, however urban resilience can be defined as “the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience” (Resilient Cities Network, n.d.). Cities endure a wide variety of challenges and changes, ranging from homelessness, accessibility and gentrification to extreme weather, earthquakes and sea level rise. In this paper, the focus is on a city’s resilience to natural hazards, such as extreme weather and temperatures, flooding, earthquakes and other meteorological, hydrological and/or seismic events. Communities have developed many analog and digital methods and tools for building resilience, but with growing urban populations and a climate crisis underway, could CDTs offer innovative methods for building resilience in urban environments?

This has been implemented to varying extents in places around the world, and shaped by each local context. In North Carolina, USA, an interdisciplinary team of researchers developed one such solution:

> MUNICIPAL is a "tool that predicts damage to infrastructure components for a specified storm event, produces an optimal restoration plan based on restoring critical services taking into account the interdependencies that exist between systems, and displays the results by means of a geographic information systems (GIS) interface"
> (Little, Loggins & Wallace, 2015, p. 1).

While not the 3D city visualization that comes to mind when imagining CDTs (see figure 4), MUNICIPAL combines digital twins of relevant urban systems to support decision-making for recovery from hurricanes. Another example is the GreenTwins project: a research collaboration that involves citizens, academics, ecologists, developers, city planners and other experts to develop and incorporate the modelling of the natural environment into the CDTs of Tallinn and Helsinki, and beyond (Petrone, 2021). Laura Mrosla, one of the researchers in the project, expressed that urban greenery is currently missing from CDTs, even though it can play a key role in hazards such as flooding, microclimate, urban biodiversity and air quality (personal communication, 17 August, 2022). One of the outcomes of GreenTwins will be a plant library containing algorithmically modeled plants that can be implemented into the "urban digital twins" of cities.

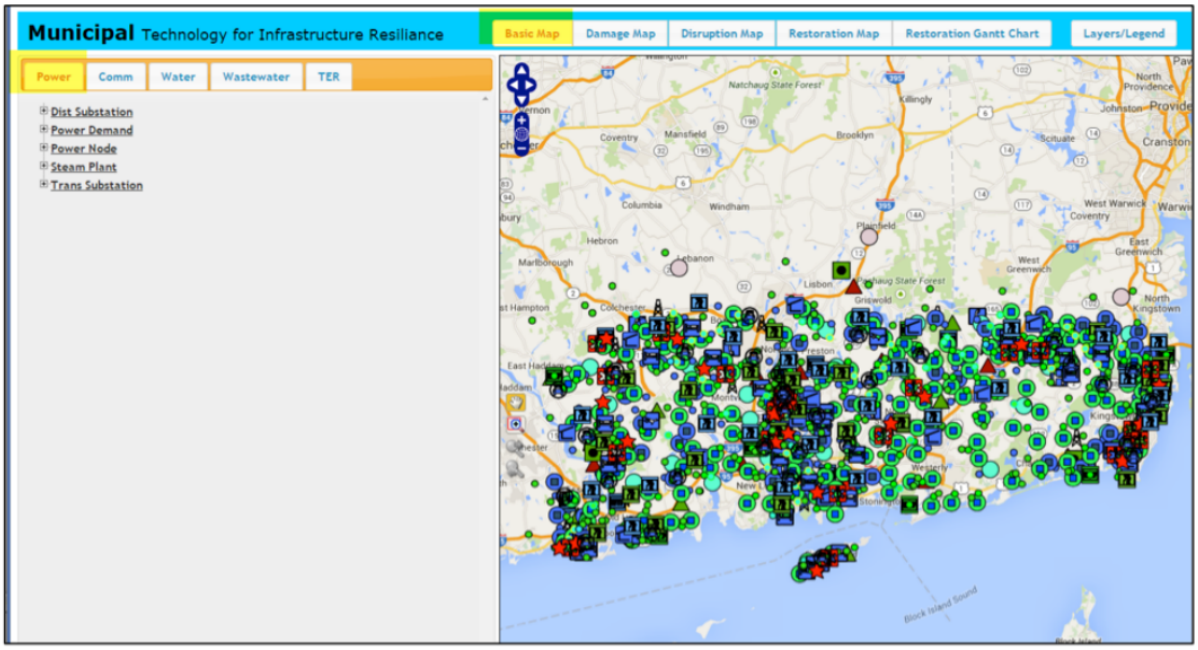

Figure 4. MUNICIPAL
(Emprata, n.d.)

Vancouver, Canada, faces the risk of heat waves, earthquakes and other natural hazards, and has been pushing forward on significant resilience planning without the help of a CDT (City of

Vancouver, 2019). According to Katia Tynan, the City's Manager of Resilience and Disaster Risk Reduction, CDTs could be invaluable tools for (1) improving the municipality's understanding of complex and multifaceted issues, (2) expanding its ability to imagine and visualize possible futures, and (3) facilitating meaningful public consultation and engagement to shape decision-making (personal communication, 15 August, 2022). These potential benefits are simultaneously some of the most challenging aspects of CDT implementation, and will be explored in more detail in the rest of this section.

3.1 Comprehending Complexity

Ford & Wolf (2020) emphasize that natural hazards in an urban environment are by nature complex and interconnected: "[d]isasters severely stress community system interdependencies by damaging or destroying built infrastructures, dislocating populations, and disrupting individual systems and their interactions" (p.1). Yet, they note that many existing disaster management models do not capture this complexity, either because they focus on modelling one specific event in an isolated way, they do not consider the iterative aspect of disaster recovery and the evolution of a situation over time, or they lack the connection between different infrastructure systems. In a City Digital Twin (CDT), the emphasis is not only the creation of isolated models, rather enabling a better understanding of the various phenomena caused by a hazard, and how they interact with each other. For example, while the modelling of floods typically focuses on hydrological models, this approach does not provide a full picture of their consequences on society (Ghaith, Yosri, & El-Dakhakhni, 2021). Ghaith et al. (2021) demonstrate that a CDT offers a way to model and simulate the interactions between water, power, transportation and the City Information Model to better understand, prepare for, and respond to flooding, as shown in figure 5.

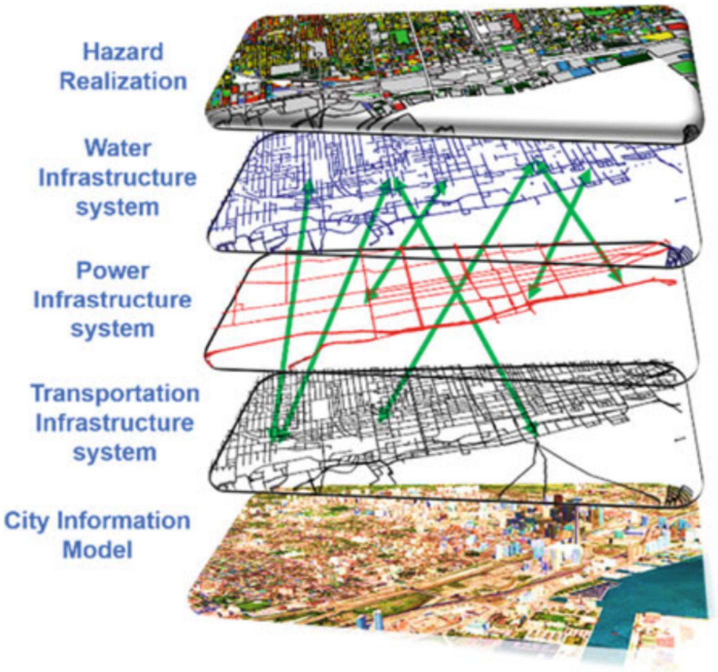

Figure 5. Modelling the complexity of flooding in a CDT (Ghaith et al., 2021, p. 581)

Considering that disaster management involves the collaboration of stakeholders who may not otherwise work together, such a tool could deepen actors’ understanding of the complexity and interdependencies of disaster events, and the work that is needed to restore crucial infrastructure (Little et al., 2015). For example, the City of Vancouver recently conducted an engagement process to inform its heat resilience planning, which involved the use of 2D printed maps informed by numerous datasets such as temperature, tree canopy, social vulnerability, cooling centers and emergency hospital visits (K. Tynan, personal communication, 15 August, 2022). According to Tynan, the use of maps and data as a tool for discussion with participants enabled the creation of compelling visual representations of the challenge at hand, and the discussion informed key priorities, such as where to place new cooling facilities. Building on this experience, Tynan expects that a CDT would deepen this engagement and analysis process, by increasing the granularity of the model, offering a 3D perspective (e.g. by giving insight into which areas have high rise buildings above the tree canopy), and generating an even better shared understanding of the challenge and tradeoffs involved. The ability to work with a CDT that reflects real-time conditions in a city could help community members and municipal employees collectively assess the situation based on real-time sensor data and qualitative community knowledge, and identify pressing needs.

The complexity that makes CDTs such a rich tool is simultaneously one of the most challenging aspects of their implementation. Unlike a digital twin for a specific object, a CDT involves modelling unpredictable phenomena at many different levels and scales of information; a somewhat chaotic collection of urban data serves as input to the CDT, which must decipher the data and make it understandable for the users (M. Zhu, personal communication, August 10, 2022). It is also important to note that a CDT, even if very sophisticated, is still not capturing all the details of the real world, and developers must make decisions about what is included, and what level of complexity is needed. For example, in some cases, building energy consumption models may be most meaningful at the neighbourhood level as opposed to the city-wide scale (Orozco-Messana, Iborra-Lucas & Calabuig-Moreno, 2021). Another example is the modelling of vegetation: living organisms are extremely complex in how they develop and change over time, and it therefore becomes important to determine which aspects are needed and possible to integrate into the CDT (Mrosla, personal communication, 17 August, 2022). How do climate change or air pollution, for example, affect the health and growth of trees? How to measure and model urban biodiversity? How to track the change in vegetation over the seasons and their interactions with each other? According to Mrosla, these are just some of the many questions about urban vegetation that could be explored with the help of a CDT. Regardless of which phenomena are included, a bigger question remains constant: in what way(s) can city dwellers understand how changes in (green) infrastructure will impact the rest of the urban systems?

3.2 Imagining Possible Future(s)

A key capability of City Digital Twins (CDTs) goes beyond the understanding of the present, to explore possible future scenarios. The simulation capabilities of a CDT provide a novel way to evaluate interventions (or lack thereof) to observe the impact on the urban environment: it is a low-risk environment in which potential decisions can be tested (Ford & Wolf, 2020). According to Ivanov et al. (2020, p. 180-181), the computer models in a CDT can be divided into three classes which can be combined in different ways:

- “Physical models:” focused on modelling current physical processes, such as the movement of air around buildings.
- “Optimization models:” given a range of targets and constraints, enable users to find a function that provides optimal solution(s), such as optimal placement of green spaces for maximum cooling and connectivity.
- “Simulation models:” make use of physical models and optimization models to conduct experiments by making modifications, such as introducing a new green space into the city, and observing the impact.

The type of experimentation that already takes place in CDTs varies widely. One example is the introduction of architectural competition building design submissions into the cityscape, simulation and visualization of their impact (Schrotter & Hürzeler, 2020). There are also larger scale complex simulations as described in the following example:

> “The [Extreme Weather Layer], combining the [urban drainage system (UDS)] digital twin with the GIS system, aims to assist city governments in analyzing the impact of climate change and new developments on the existing infrastructure, as well as the concurrent flooding risk at both a single plot and at the city scale. Once the data on UDS, rainfall, land use, topography and soil type are known, the hydraulic modelling software [...] can be used to ascertain which manholes in the urban area are vulnerable to intensive rainfall and cause flooding on the streets.”
>
> (Truu, Annus, Roosimägi, Kändler, Vassiljev & Kaur, 2021, p. 9)

The availability of such simulations can support urban planners, who must take into account a large variety of resilience considerations in their work. For example, planners in Singapore are expected to consider urban canopy in their plans, without necessarily having specialized knowledge of urban climatology: the highly developed Virtual Singapore CDT enables the integration of Building Energy Simulation and Urban Canopy Modelling to support their designs (Deng et al., 2021). Overall, CDT simulations enable planners to experiment in the digital sphere before changes are implemented in reality: “the goals of DTs are to reduce failures from real-world projects” (Park & Yang, 2020, p.4).

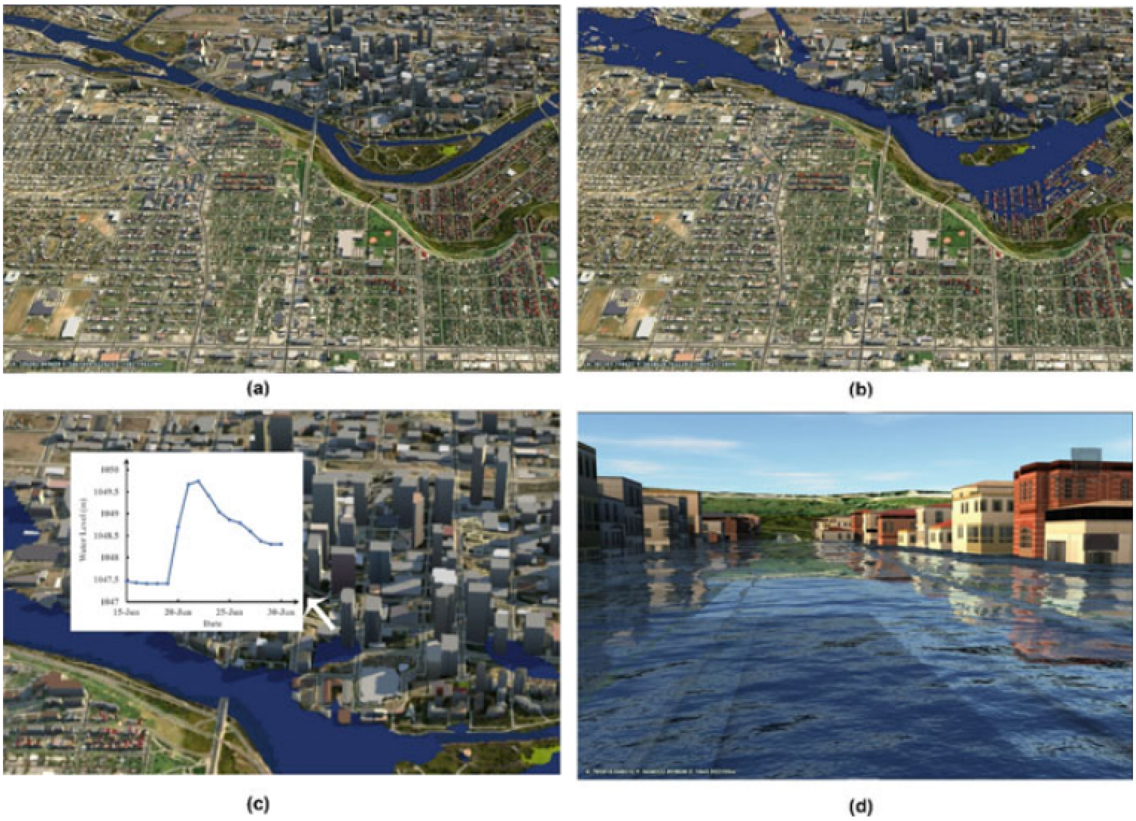

Fig. 7 City digital twin visualization: **a** Bird-eye view of part of the city on June 15th before flood **b** Bird-eye view of same part of the city on June 23rd **c** hydrograph at one of the buildings **d** Human-eye view of the flooded buildings

Figure 6. Calgary CDT flood simulation
(Ghaith et al., 2021, p. 586)

As shown in figure 6, in the case of disaster management, such experimentation can play an important role in practising high risk scenarios before a hazard actually threatens the community. In the case of the North Carolina disaster management tool MUNICIPAL, service providers were previously concerned with restoring their own individual systems (e.g. water, power, communication) after a storm; however, “[r]ather than just focusing on a single incident and the restoration of a particular infrastructure service, [MUNICIPAL] seeks the rapid restoration of the critical facilities (i.e., hospitals, emergency services, water, food, and fuel distribution points) necessary to serve the community” (Little et al., 2015, p. 7). As a result of the simulation tool, “MUNICIPAL could demonstrate to independent service providers how the overall community resilience would benefit if priority were given to those actions necessary to restore functionality to the critical facilities,” such as focusing all infrastructure efforts around hospitals in the city (p. 7). This led to a profound shift in the approach to disaster recovery among the various stakeholders, a shift that could be implemented at the next storm event.

Decision-makers are not the only stakeholder group that benefits from imagining the future via CDTs. It can be challenging for community members to fully understand complex issues that affect their cities, which may not be visible, immediate or within their realm of experience. CDTs offer another tool to help make meaning out of complex and interdependent systems and act as a bridge between factual information and visual storytelling. (K. Tynan, personal communication, 15 August, 2022). Physical hazards are the most commonly modelled phenomena, and "visualizing the non-physical systems and human interactions is a significant challenge" (Shahat et al., 2021, p. 13-14). However, CDTs offer innovative methods to make the invisible visible. For example, "Faircare Verkehr" is a storytelling tool developed as part of the Hamburg CDT: the prototype (see figure 7) guides users to learn about unpaid care work, the people who do it and the distances they cover, with the aim to encourage a better understanding of the accessibility gaps that exist for caregivers (R. Herzog, personal communication, 9 August, 2022).

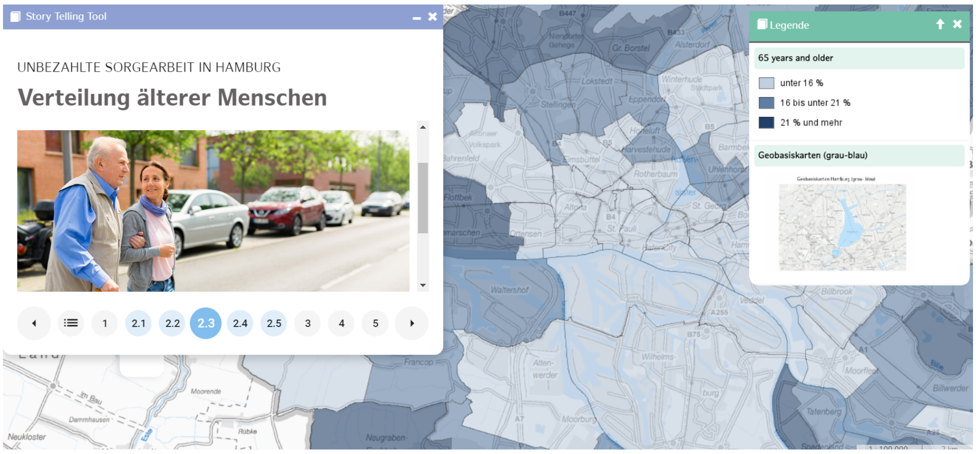

Figure 7. Screenshot of the Hamburg CDT Story Telling Tool
("FairCare Verkehr," n.d.)

A particular strength of CDTs is their emphasis on effective visualization: "[o]ver several decades, geovisualizations have evolved into highly realistic, interactive (and in some cases immersive) digital environments that allow for greater data exploration capabilities and new knowledge discovery," which can influence risk perception among users (Goudine, Newell, & Bone, 2020, p.2). One frequently misunderstood area is green infrastructure: people are often not aware of the importance of vegetation in cities, and CDTs can offer a way to demonstrate its impact on human wellbeing and the ecosystem as a whole (L. Mrosla, personal communication, 17 August, 2022). According to Mrosla, visualizing the role of trees on urban phenomena, such as cooler microclimates, reduced noise pollution or biodiversity, and their vulnerability (e.g. it would take 10-50 or more years, depending on the species, for a tree to grow back fully) could inform residents' decision of whether or not to cut down a tree in their neighbourhood, and how to design and maintain their private gardens. In the case of less frequent yet severe disasters, CDTs can visualize events in a 3D environment and make them more tangible; this is the case in the Calgary CDT, which enables users to view the extent of flooding from a human-eye view (Ghaith et al., 2021).

Beyond simulating and mitigating risks, CDTs could offer a space to encourage imagination and creativity in the resilience-building process, and a positive representation of what cities could become (K. Tynan, personal communication, 15 August, 2022). For example, given the worst-case earthquake scenario in Vancouver, what would an equitable rebuilding of the city look like? More broadly, how can communities shape collective visions for the future they want? In practice, how do decision-makers navigate trade-offs and priorities in complex situations?

3.3 (Re)acting Together

One important way in which CDTs can help manage trade-offs is facilitating hazard-related decision-making processes in multi-stakeholder environments. This can take the form of cross-disciplinary or cross-field collaborations and/or the engagement of community members in planning practices. The decisions being facilitated may be future-oriented mitigation or recovery plans, or may focus on (training for) real-time response to disasters. When formulating long-term plans for a city and dealing with hazards, there are always trade-offs that must be made (K. Tynan, personal communication, 15 August, 2022). For example, the City of Vancouver aims to densify its residential areas, yet the least dense residential neighbourhoods are also the ones with the most tree canopy cover: which of these competing interests should be prioritized? According to Tynan, CDTs can help to understand possible choices and inform decisions by gathering insight on the trade-offs that community members are willing to accept and simulate those choices so that their impacts can be observed, and the decisions can be iteratively modified before implementation (see figure 8).

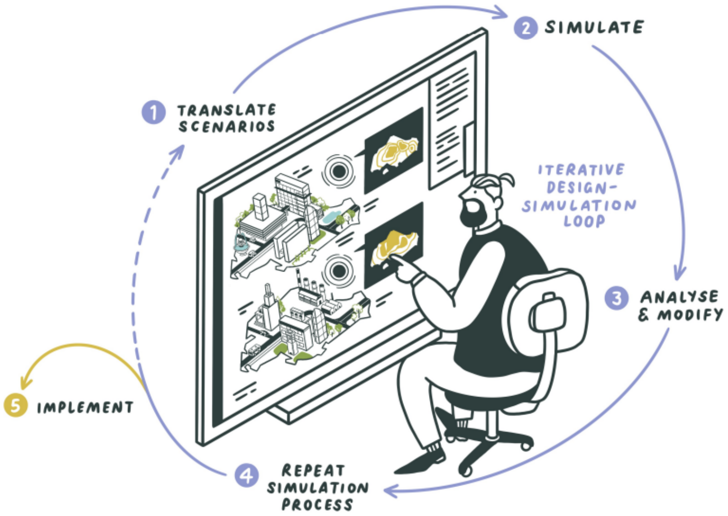

Figure 8: Iterative nature of simulations in CDT (Aydt, 2020, Image: Idea Ink, 2020)

In a “Map Your Neighbourhood” workshop organized by Vancouver’s Resilience Team, a mutual exchange occurred in which participants used maps to identify and share their knowledge of the assets located in their neighbourhoods, and the City shared existing data (and knowledge gaps) regarding the challenges faced by the City (K. Tynan, personal communication, 15 August, 2022). This two-way sharing and transparency played an important role in building trusting relationships between community members and local government. The immersive, realistic and interactive aspects of CDTs can enhance such community engagement processes in active and meaningful ways (Schrotter & Hürzeler, 2020). For instance, it can be challenging for community members with limited experience reading 2D plans to use maps, or they may find it challenging to imagine an issue or idea in 3D: a CDT explored in Augmented Reality (AR) or Virtual Reality (VR) allows participants to walk virtually through the city and discuss different challenges in a tangible way (L. Mrosla, personal communication, 17 August, 2022). How can planners make space more comfortable for people during heat waves? In a CDT environment, Mrosla explains that participants can make their own suggestions, test how they affect the city, and be prompted to think and discuss the complex challenge.

In many cases, the CDT enables the involvement of demographics that may not otherwise participate. For example, in Switzerland, the Zurich CDT served as the foundation for a Minecraft-style game that attracted a younger crowd to design and submit ideas for the planning of the city (Schrotter & Hürzeler, 2020). In Herrenberg, Germany, the CDT includes an air pollution simulation: users can add streamlines or make modifications to the urban environment and observe the impact on air pollution, as shown in figure 9 (Dembski et al., 2019). By integrating the CDT with VR technology, the Herrenberg team could “involve citizens with migration and different language background[s], groups of elderly people and even deaf and otherwise challenged participants. All of these are marginalized groups that are commonly not included into urban planning citizen participation” (p. 9). Over 700 participants interacted with the VR tool prototype and a survey of participants indicated a positive response; participants found the experience interesting, beneficial, understandable and entertaining.

Figure 6. Particulate matter and wind flow simulation visualized in the CAVE. The particulate matter concentration is represented as an iso-surface. For the wind flow simulation, the color range from blue to green indicates wind speed from low to intermediate. The CAVE is a stationary five-sided cube for VR back-projection run by a 22-node cluster, five 3D-projectors, a tracking system, and active shutter glasses for the participants (photo credited to Wössner, 2017).

Figure 9. VR interaction with the Herremberg CDT
(Dembski et al., 2020, p. 11)

Beyond long-term resilience planning, CDTs are relevant to real-time response to disasters. For instance, “3D geo-data can be used in disaster management and emergency response because they may provide valuable information such as the location of building entry points [305,306]. In this context, 3D city models can be used to determine the best position for the deployment of the ladder trucks before the arrival of firefighters at the scene” (Biljecki, Stoter, Ledoux, Zlatanova & Çöltekin, 2015, p. 2859). This 3D real-time data is crucial for saving lives, and also for protecting economically important infrastructures and products, especially when multiple stakeholders are involved. In the

Port of Tyne, cargo is transported in and out daily: the port authority is liable for cargo when a vessel is coming or out of the port, and once the cargo is in storage, the client is responsible for it (M. Zhu, personal communication, August 10, 2022). Considering this shared responsibility, and the fact that infrastructural operators have specialized knowledge of the region and their industry, Zhu explained that a digital twin of the Port will be an important planning tool to respond to natural hazards that could threaten the area. It is not enough for the CDT to guide real-time response; dialogue and communication is also key:

> “Developing successful strategies for restoring services following an extreme event requires that these interactions be understood by all involved stakeholders and confirmed through education and training. Successful collaboration requires that dialogs be initiated and sustained between and among the various stakeholders using terms of reference that all can relate to and act upon” (Little et al., 2015, p. 2)

Given the value of practising the process of collaborative problem-solving, Little et al. (2015) observe that online and digital simulation tools can offer a lower cost, more accessible platform than in-person tabletop exercises.

Overall, the value of CDT for disaster management becomes quite apparent, as it can combine updated data from multiple sources in real-time to model the complex acute and long-term hazards at play, enables the prediction of how decisions will impact the community based on the specific context and the type of disaster in question, and act as a tool to facilitate interdisciplinary and cross-stakeholder decision-making in the short- and long-term (Ford & Wolf, 2020). In addition to these benefits, Ford & Wold (2020) state that CDT for resilience planning can be seen as a “microcosm” for CDT development, integration and application: since disaster management requires complex integration of multiple systems, a CDT developed in the disaster context will be relevant to everyday urban planning decisions, and its impact will be measurable and tangible. The next section explores some of the technical considerations in the development of a CDT.

4. Implementing a CDT for Resilience Planning

In the previous section, the potential for CDTs to support urban resilience was explored. In this section, the paper presents key considerations that inform the technical implementation of a CDT, based on examples of CDT research and development. Rico Herzog is an Urban Data Scientist at HafenCity University Hamburg and he is currently involved in the Connected Urban Twins (CUT) project a collaboration between Hamburg, Leipzig and Munich which began in 2021 and aims to “jointly advance the development of digital twins for cities and municipalities” (Connected Urban Twins, n.d.). As one of the researchers on the project, Rico Herzog is the lead of modelling and simulation, and is currently conducting a survey to determine which departments of the Hamburg municipality are already using models (personal communication, 9 August, 2022). The goal of the project is to better understand the needs and potential for integrating different modelling efforts into a future CDT, before focusing on its development. The development of a CDT involves data harvesting, data modelling, and data visualization; with many platforms, data sources and models available, the key challenge is transforming chaotic input into one useful tool (M. Zhu, personal communication, August 10, 2022). This section highlights some considerations in the development process including (1) setting priorities, (2) collecting and managing data, (3) integrating diverse models and (4) adapting to user needs.

4.1 Setting Priorities: Hazards and Users

The first step in a CDT development, as illustrated by Herzog's role in the Connected Urban Twins project, is conducting research and making decisions that shape the priorities of the platform. Considering the high complexity and cost of a CDT, it is common for CDTs to begin with a few foundational layers, and then build over time. Which hazards are the most urgent to tackle? Which phenomena are crucial to include right from the first prototype? Municipalities often begin by identifying the key infrastructure systems to be modelled given the location and the hazards, or themes, being prioritized (Ghaith et al., 2021). Some examples of thematic CDTs include Singapore's emphasis on the urban heat island effect (Haydt, 2021), Tallinn and Helsinki's research on modelling green infrastructure (L. Mrosla, personal communication, 17 August, 2022), modelling carbon emissions in Jeonju (Park & Yang, 2020), and preparing for flooding in Calgary (Ghaith et al., 2021). In addition to decisions about the data and models needed, municipalities may also consider the type of interactivity that should be included. The future CDTs of Hamburg, Munich and Leipzig will likely have a modular architecture: a georeferenced city model with different modules that can be added, such as a participation module, VR module, different subsystems, and "build your own twin," to cater to different interaction needs (R. Herzog, personal communication, 9 August, 2022).

To determine the type of interactivity, developers must ask: who are the users of the CDT? And more broadly, what are the social priorities of the project? Dembski et al. (2020) advocate for "people-centred" technology for the planning and management of cities, as a way of "giving back sovereignty of the data and access to information to the citizens" (p. 4). One important aspect of people-centred technology is ensuring that stakeholders can meaningfully engage with the CDT: in the case of the MUNICIPAL disaster management platform, the research team prioritized the building of relationships with emergency responders, infrastructure providers and local government to understand the context and better inform the development of the software (Little et al., 2015). In some cases, meeting the needs of different stakeholders may mean developing different facets designed for different users: in the case of the Hamburg CDT, this will likely involve creating some modules for public servants and different ones for community members (R. Herzog, personal communication, 9 August, 2022). Importantly, the analytics embedded in the CDT must be well-developed, transparent and accessible by developers and policy makers (Park & Yang, 2020) to ensure that users understand the data and results that they are using.

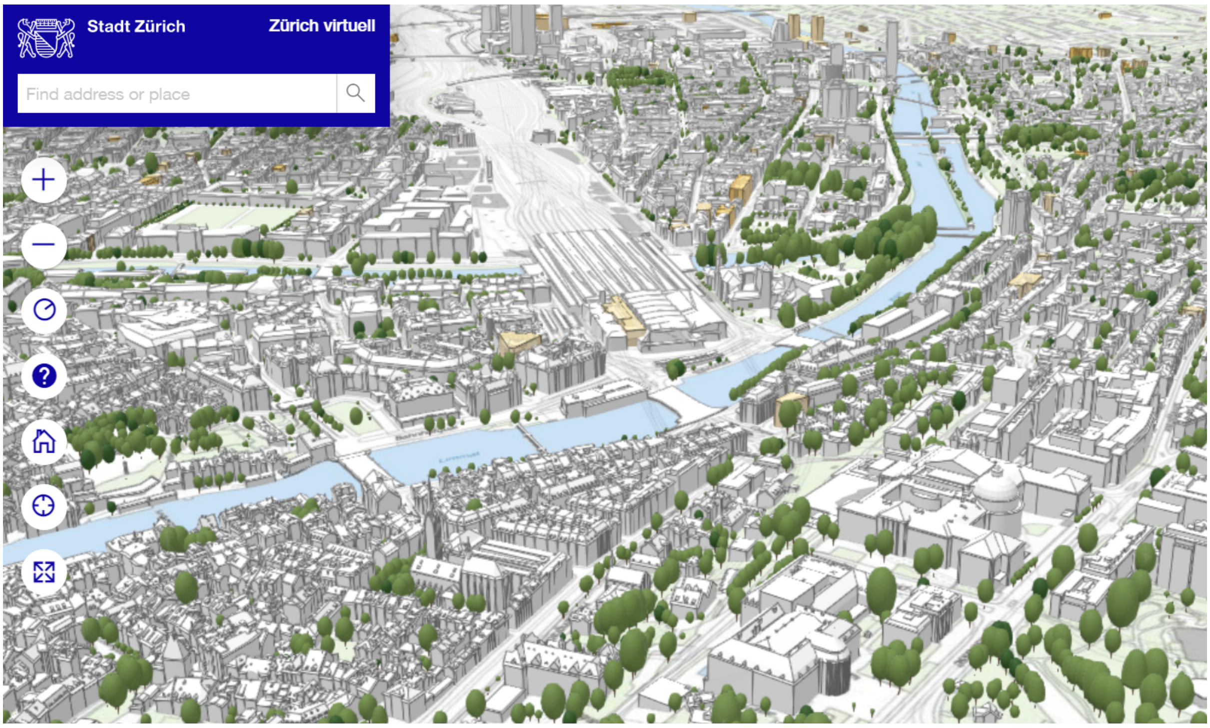

Figure 10. Zurich CDT
("Zürich virtuell", n.d.)

According to Schrotter & Hürzeler (2020), to make a CDT fully accessible, datasets must be open and the software must be open source; this allows for future analysis, visualization and the development of new applications. This openness can prompt creative interactions with the fabric of the city. For example, as a result of Zurich's open source CDT (figure 10), Blindflug Studios AG developed the free game "(re)format Z:" which explores the Reformation in Zurich in a "dystopian cyberpunk version of the city" (p. 105). Developing open software can be challenging in the public sector due to limited financial and human resources (L. Mrosla, personal communication, 17 August, 2022). As a result, early CDT developments may begin on an enterprise platform (e.g. Esri) to launch a product within funding timelines. According to Mrosla, a big question among researchers then becomes: how to stay independent from the software to be able to change it in the future, and avoid vendor lock-in? Questions around open software are closely tied to concerns around stewardship: according to Herzog, the prototypical development of software is not the limiting factor any longer, but determining who maintains the CDT once it is developed, who is responsible for the code, security, hosting and funding, are all very challenging aspects that are crucial to figure out to ensure a sustainable stewardship plan (personal communication, 9 August, 2022).

4.2 Collecting and Managing Data

The next step in developing a CDT is the establishment of a data infrastructure. Based on the priorities described above, developers must "determine and acquire the data needed to build, calibrate, and validate" the necessary model(s) (Ghaith et al., 2021, p. 580). First, the City Information Model must be constructed as the foundation of the platform: this is the "background" data that will be used for visualization and simuations of the city, including aspects such as buildings, roads and land cover. Different cities construct this foundation in different ways. The Kalasatama

Digital Twins Project aimed to create a CDT of a neighbourhood in Helsinki, and the City Information Model was constructed as two separate components: a reality mesh model and a semantic CityGML model (Helsinki, 2019). The project report describes the reality mesh model as a photo-realistic triangulated surface that was generated from 2,083 aerial photos. The use of the ContextCapture software made this modelling step simple for the project team (see figure 11), however the processing of such a large dataset was extremely computationally intensive and the neighbourhood was divided into tiles in order to model smaller subsets at one time.

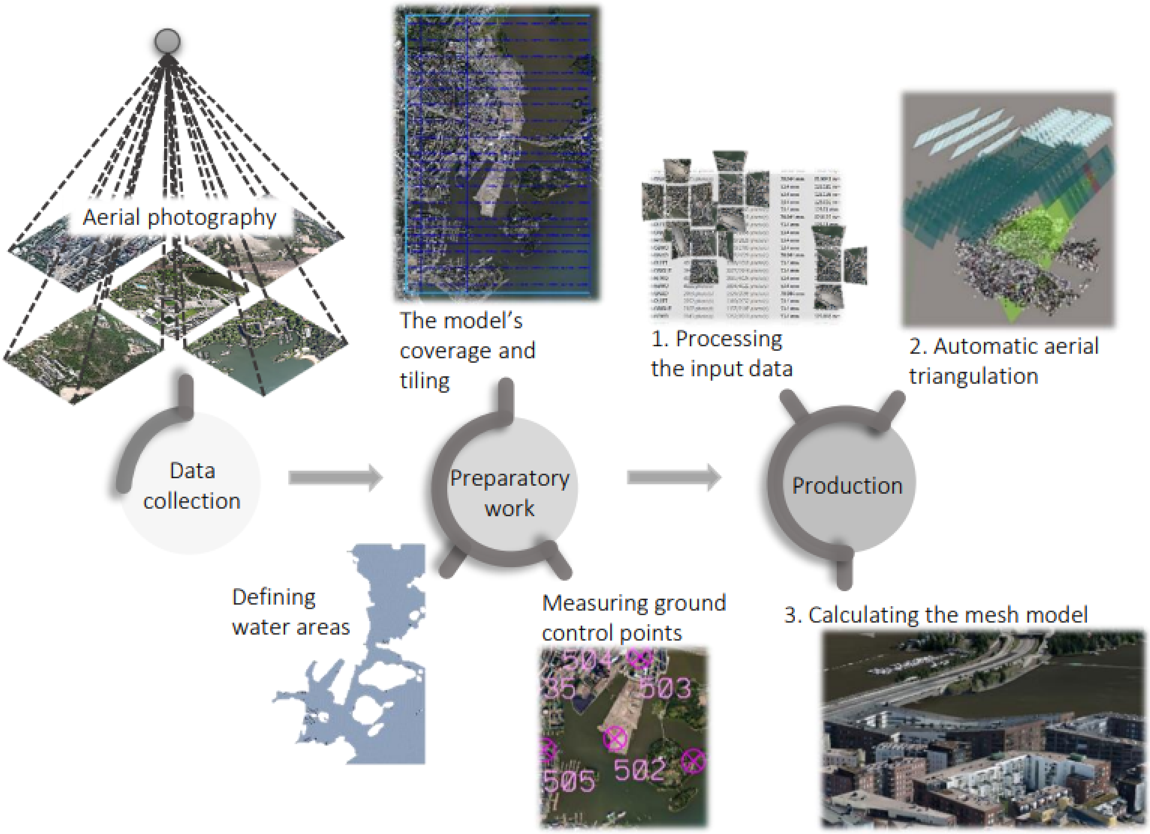

Figure 11. Creation of the reality mesh model for Helsinki CDT (Helsinki, 2019, p. 6)

The second component of Kalasatama's City Information Model, the semantic CityGML model, follows an open, international standard set by the OGC for 3D urban datasets (Helsinki, 2019). Each object in the model contains data about its geometry, topology, semantics and appearance, and objects can include existing buildings, planned buildings, bridges as well as other features such as the ground and waterways (Open Geospatial Consortium, 2021). In order to be valid, objects in the CityGML must be watertight and without geometric or topological errors, enabling GIS applications such as wind simulation. However, building-level design and simulations (such as building energy consumption) are usually carried out with Building Information Modelling (BIM) and this is a significant challenge for CDT development:

> "The GIS and BIM models overlap with city information modelling, but each has its own focus. The BIM data focuses on building and construction design aspects and construction information and therefore it includes a very rich semantic and detailed information model of

> the building's internal and external physical elements. GIS data, on the other hand, broadly describes environmental information at different times, making the data less detailed, but the possibility and the need for regular updating is essential.”
> (Helsinki, 2019, p. 56)

The question of how to successfully integrate BIM into a City Information Model has been posed many times in CDT research (e.g. Schrotter & Hürzeler, 2020; Park & Yang, 2020; Biljecki et al., 2015). To build the CityGML, the Kalasatama project team extracted building roof and footprint data from CAD files, and used the BRec software to reconstruct watertight 3D models of buildings using the city’s Digital Terrain Model and Digital Surface Model, as shown in Figure 12 (2019).

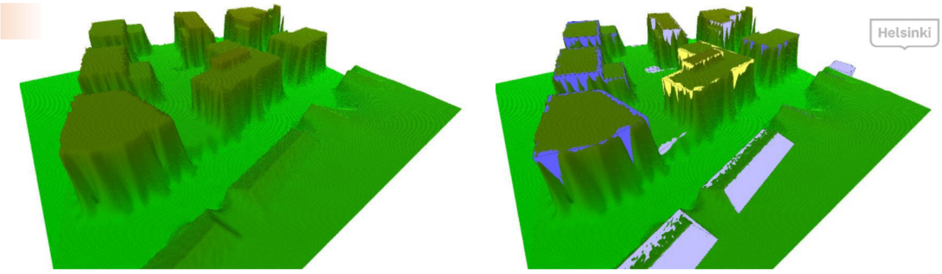

Figure 24. Step 1: DTM and DSM (application: BRec)

Figure 25. Step 2: Buildings fitted into the DTM and DSM

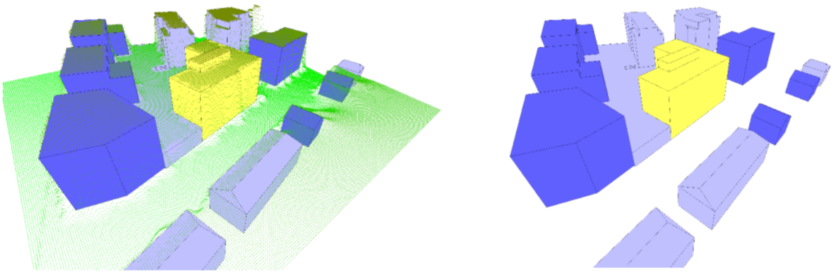

Figure 26. Step 3: Examination utilising the point cloud

Figure 27. Step 4: The resulting CityGML buildings

Figure 12. Creation of the CityGML model for Helsinki CDT (Helsinki, 2019, p. 22)

Once both components of the City Information Model were constructed, they could be visualized simultaneously for a realistic and semantically correct CDT interface (see Figure 13). In some cities, building this foundation for the CDT is a significant barrier. For example, in the City of Vancouver, there is a lack of data about the city’s buildings, infrastructure and basic environmental phenomena such as local aquifers, let alone 3D datasets (K. Tynan, personal communication, 15 August, 2022). Without good data foundations, it is impossible to build a CDT that could inform decision-making at the level of detail and precision that would be expected. However, according to Tynan, working towards a CDT and demonstrating the value of real-time, complete and high quality data may actually help the municipality to prioritize allocating staff and resources to the maintenance of city-wide data that supports local resilience (personal communication, 15 August, 2022).

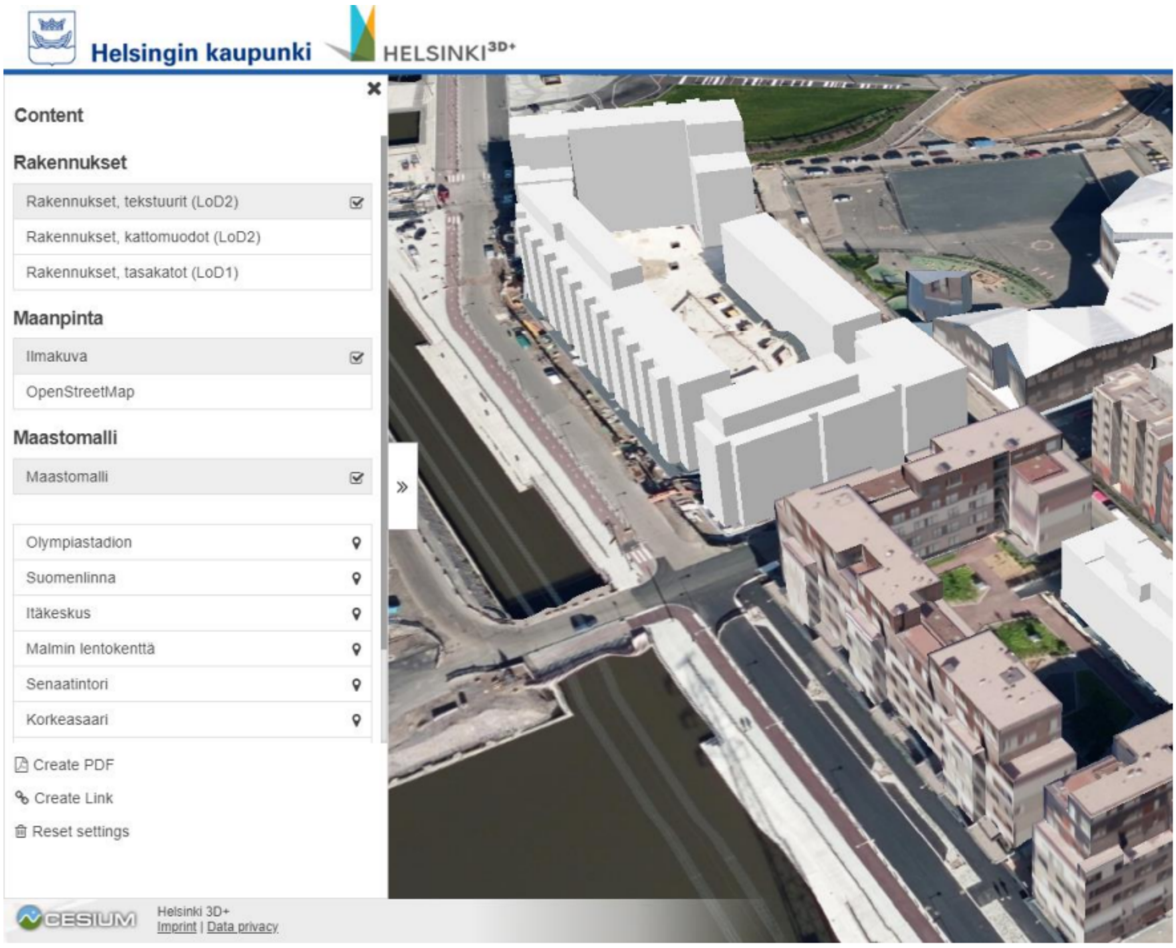

Figure 17. Browser view of kartta.hel.fi/3d web site, where 3D city information model is being updated

Figure 13. Combining reality mesh and CityGML to model buildings in Helsinki CDT (Helsinki, 2019, p. 18)

Once the City Information Model is established, data for monitoring and simulation of hazards must be collected and integrated into the digital twin layers. The sources of this data will vary depending on the hazards being modelled, and the availability of data; it can be retrieved from a combination of API services, Internet of Things (IoT) devices and static information (M. Zhu, personal communication, August 10, 2022).

In the most dynamic version of the CDT concept, the platform has “the ability to receive and effectively process data flows collected automatically through distributed “Internet of Things” (IoT) sensor systems. The DT of the city is gradually filled with the data of the real city, collected in real-time from deployed IoT infrastructure and urban information systems” as shown in Figure 14 (Ivanov et al., 2020, p.178). Based on this understanding of the CDT, the quality of analyses and decision-making support is completely dependent on the quality and availability of data on the urban phenomena that are to be modelled. The increasing need for, and interest in, dynamic data is reflected in the latest version of CityGML (3.0) which has incorporated two new modules focused on changing phenomena:

> “The Versioning module manages changes that are slower in nature. Examples are (1) the history or evolution of cities such as construction or demolition of buildings, and (2) managing multiple versions of the city models. The Dynamizer module manages

higher-frequency or dynamic variations of object properties, including variations of (1) thematic attributes such as changes of physical quantities (energy demands, temperature, solar irradiation levels), (2) spatial properties such as change of a feature's geometry, with respect to shape and location (moving objects), and (3) real-time sensor observations. The Dynamizer module allows establishing explicit links from city objects to sensors and sensor data services." (Open Geospatial Consortium, 2021)

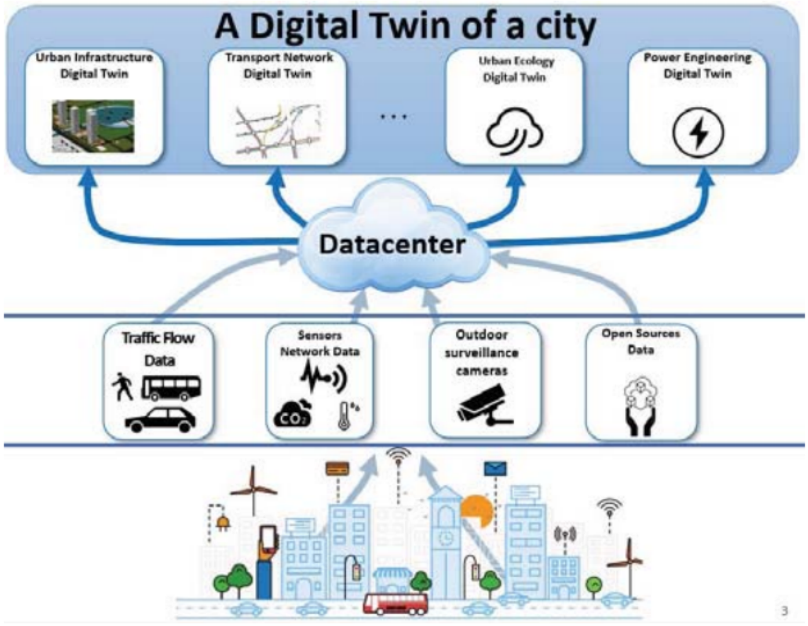

Fig. 1. An example of the interface's appearance

Figure 14. Conceptualizing a CDT data infrastructure
(Ivanov et al., 2020, p. 179)

While lacking data is a challenge in some places, in others there is sufficient data but lacking understanding of how to use it (M. Zhu, personal communication, August 10, 2022). For example, efficiently updating both the City Information Model and the hazard data in the CDT is challenging (Schrotter & Hürzeler, 2020) yet particularly important when it comes to time-sensitive and high risk phenomena. According to Shahat et al. (2021), managing large amounts of data from various sources also poses a significant challenge, and this can be addressed by developing different layers for different data types. However, they explain that models must be made interoperable in order to enable a fully integrated CDT, therefore developing frameworks to standardize data and sharing frameworks across applications and models would help to address this challenge.

4.3 Integrating Models

When it comes to digitally representing hazards in the urban environment, there are many existing models that simulate specific phenomena; for example, Virtual City Systems GmbH is a company employed by municipalities to develop models of the urban heat island, bomb blast, flooding, sea level rise, wind, and other phenomena (R. Herzog, personal communication, 9 August, 2022). Herzog explains that, in a CDT environment, the potential lies in integrating existing models, which are often developed in specialized silos, into one cohesive system. Most CDTs build layers of models upon the City Information Model and integrate them with each other (Ghaith et al., 2021). The challenge is enabling the different models to interact with each other, in other words, facilitating their interoperability (Shahat et al., 2021).

To manage this translation, developers can implement "interoperability translators," software that regulates how systems interact with each other (Ghaith et al., 2021). For example, in the case of the Calgary-based CDT designed to model floods, "simulation results will be sent back and forth between the simulation models and the translator software (e.g., GIS) until a steady state results are achieved" (p. 581). Taking this interaction between models even further, Ford & Wolf (2020) emphasize that CDTs should effectively integrate the impact of decisions, community context and simulation models as "disaster management processing loops that drive iterative cycles" (p. 7), as shown in figure 15. This means that rather than reaching one steady state, the CDT is continuously updating itself based on real-time data from sensors in the city: as such, it can assist planners and responders with decision-making using a system of models that reflects reality as closely as possible.

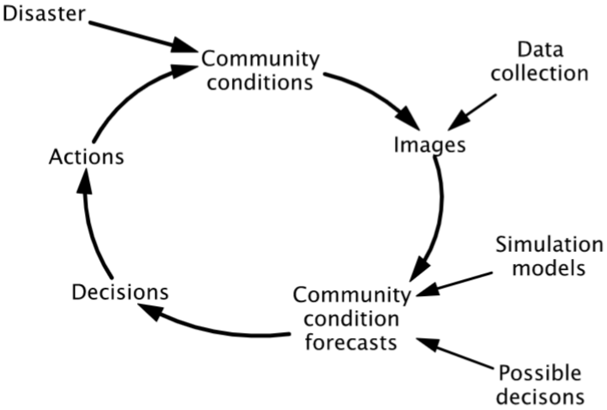

Figure 15: Model of iterative community disaster management
(Ford & Wolf, 2020, p. 2)

Another consideration in a multi-layered CDT is the high level of computing power required for running the many different models (Shahat et al., 2021). Considering that disaster management decisions may require near-real-time insight, developers need to find a balance between the accuracy of the results needed for a specific CDT use case and the computational power and time required (Ghaith et al., 2021). For example, the level of detail in visualizations could be lower for real-time disaster-response analytics that are focused on data-driven decision-making, whereas disaster training and community engagement may require that visualizations be highly detailed and realistic.

Singapore is developing the "Digital Urban Climate Twin (DUCT)" which builds upon its CDT to inform cooling strategies for the city (Haydt, 2021). According to its lead investigator Dr. Aydt, the interdisciplinary nature of climate modelling in the urban environment requires a "federation of models" that is used to run various scenarios (see figure 16). Each set of scenario parameters uses several models to carry out a simulation; the complex process of carrying out a workflow which integrates multiple models, when done manually, is time consuming and error-prone. As a solution, Aydt proposes the use of a Simulation as a Service (SaaS) middleware that acts as "software glue" that connects the different models to each other and automates complex workflows. The idea is that a user could make a simulation query using a simple interface, and the SaaS middleware would query the models needed to complete the multi-step analysis. Beyond reducing time demands and potential errors, the value of such a framework is facilitating a straightforward experience for users of the CDT.

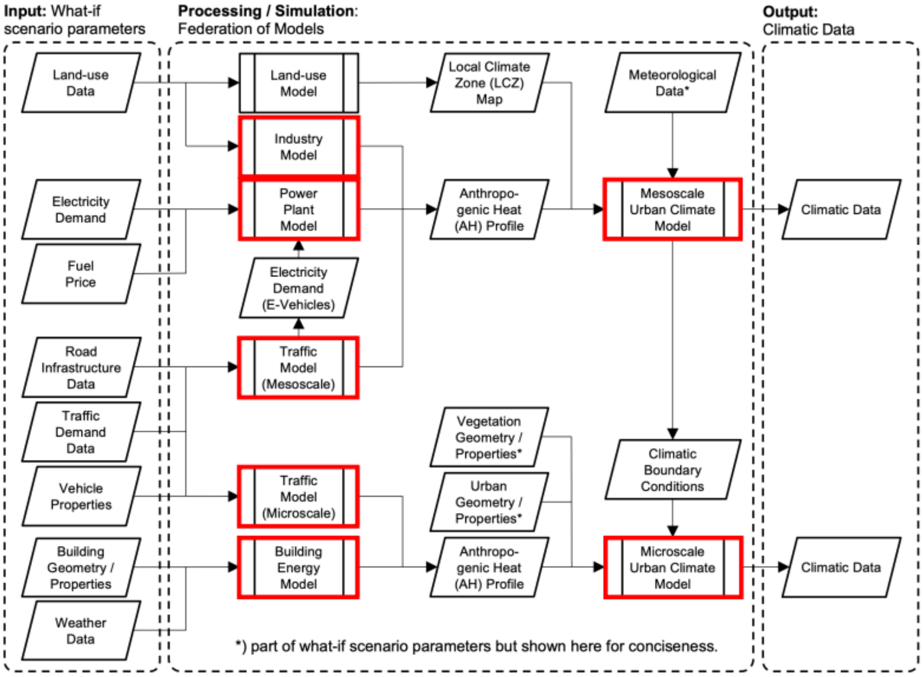

Figure 16. Federation of Models for Urban Heat Island simulation (Aydt, 2021)

4.4 Ensuring Usability

According to Zhu, the hardware and the general framework for implementing City Digital Twins (CDT) exists, but there is a learning curve when using any new platform (personal communication, August 10, 2022). He explains that people are comfortable with tools that they have been using in the past, and a technology must become easy to use in order for it to be accepted. With this in mind, social considerations around ease of use and comfort with a CDT should be prioritized in order for the technology to be widely adopted; one such example is participants' comfort with the level of privacy afforded by the technology (Shahat et al., 2021). In the case of the Hamburg CDT, developers considered naming the community-accessible module "Citizen Twin"; however, they realized that it may lead to backlash if citizens interpret it as a platform that creates digital twins of its individual citizens; they decided to search for a more suitable naming (R. Herzog, personal communication, 9 August, 2022). Another example is the user experience when visualizing the CDT. For example, during community engagement with CDT prototypes in Tallinn, participants expressed discomfort with the Virtual Reality visualization due to "cyber sickness" from flying over or walking through the digital city (L. Mrosla, personal communication, 17 August, 2022).

In addition to prioritizing comfort with using the platform, it is important to consider users' ability to understand and apply the visuals and analyses that are produced by the CDT and its means of representation. Practitioners sometimes present the results of CDT simulations without knowing what they mean or what is going on behind the scenes, and there needs to be more emphasis on having users understand the processes that they are applying (R. Herzog, personal communication, 9 August, 2022). In other words, there is often a gap between those who build models and those who use them (Little et al., 2015, p. 2) which can lead to uninformed assumptions. This is particularly worrisome when it comes to severe hazards or time-sensitive decision making. In a disaster situation, “many communities can expect to be ‘on their own’ for the first seventy-two hours” (O’Leary, 2004 as cited in Little et al., 2015, p. 5). As a result, it is extremely important that decision-support tools such as MUNICIPAL are developed with the needs of local practitioners in mind and tailored to be user-friendly when delivered” (Fothergill, 2000, as cited in Little et al., 2015, p. 5).

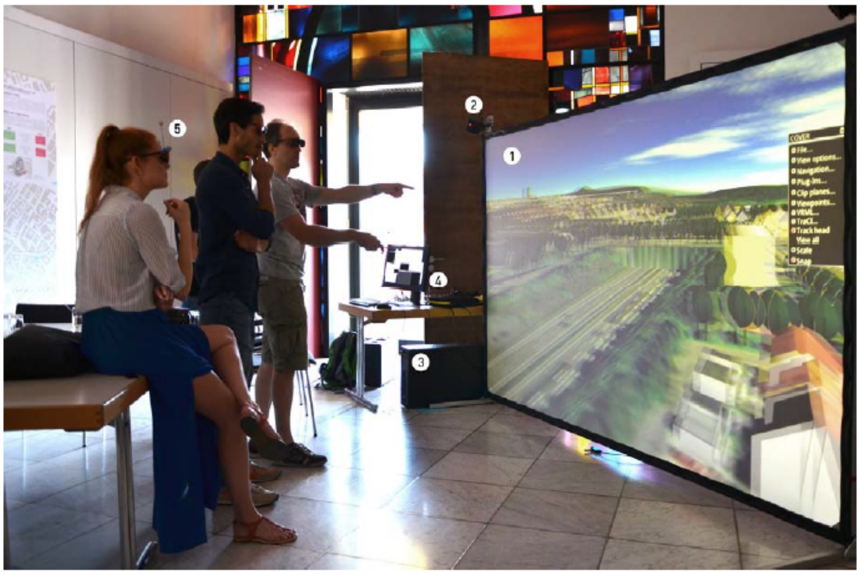

Figure 7. The mobile VR setup during a participatory process including a back-projection wall [1], tracking system [2], computer [3,4], a 3D-projector, and active shutter glasses [5] for the participants (photo credited to Dembski, 2019).

Figure 17. Herrenberg CDT VR prototype
(Dempsky et al., 2020, p. 12)

How can the usability and understandability of a CDT be improved? As mentioned previously, involving stakeholders in the development of the tool is key to its effectiveness (Little et al., 2015). Such involvement can lead to specific ideas on ways the CDT can better serve its purpose. For example, after engaging with the Herrenberg CDT prototype shown in figure 17, participants proposed improvements on the accessibility and visual aesthetic:

> “accessibility should be high, which means that citizens should be able to use the model in public (for example, in the town hall) as well as in their private life (for example, using 3D-glasses at home) [...] the graphical presentation should be better in the sense of more realism, such as in Google Earth.”
> (Dembski et al., 2020, p. 14)

The visualization aspect of CDTs is of particular significance in the case of resilience topics, as hazards being discussed may be rare or may not have been experienced by residents or decision-makers. Visualization in 3D “permits shape cognition and evaluation of complex spatial circumstances” as well as the results of analyses (Biljecki et al., 2015, p. 2854). To address the computational limitations discussed earlier in the paper, developers should consider the level of detail needed for the visualization to serve its purpose while simultaneously limiting data volume (Park & Yang, 2020). In the case of public interaction, a high level of detail is needed in order to facilitate a "spatial recognition of reality" (p.18). A detailed 3D visualization can be further enhanced with Virtual Reality technology. The CDT of Herrenberg makes use of OpenCOVER, a render module that can visualize simulations by combining multiple data sources into a projection onto the 3D city model (Dembski et al., 2019). It makes these renders visible via COVISE: "an open source modular visualization system, designed to support collaborative visualization of data in virtual environments as well as on the desktop" (p. 6).

Even when prioritizing a high level of detail, CDTs will always contain inaccuracies and errors in visualizations, as well as incompleteness when some systems cannot or are not represented (Shahat et al., 2021). There may also be tradeoffs between the level of "realism" of a visualization and the ability to use the model for simulations. For example, modelling trees using point clouds from a laser scanning (e.g. LiDAR) will lead to more realistic appearances than with other methods, but models derived from the point cloud may have limited applications in terms of simulating phenomena such as vegetation growth in the urban environment (L. Mrosla, personal communication, 17 August, 2022). Mrosla notes that when writing an algorithm for tree growth, an individual tree simulated in the CDT will look like a tree from its species, but it will not be an exact "copy" of its real counterpart in the physical environment. Combining ecological modelling with regular updating of vegetation data with satellite imagery and sensors could help find a compromise; however, a challenge for CDT developers remains: how to model and visualize uncertainties in simulations and models? In other words, how to differentiate between what is, and what might be?

The usability consideration described above will likely play an important role in tackling one of the key challenges to CDTs which Ford & Wolf (2020) refer to as "fatigue risk": considering the high cost of investing in a CDT, supporters (including public officials, funders and citizens) may withdraw their support before the benefits of the CDT are reached (p. 7). They suggest that developing a CDT for disaster management purposes may allow developers to demonstrate meaningful results relatively quickly, demonstrating the usefulness of CDTs overall and securing longer term support.

Conclusion

In a time of increasing urbanization, heightened risks from extreme weather, and developing smart technologies, this paper has explored the potential for City Digital Twins to support urban areas in building their resilience to the various shocks and stresses they face. Section 1 outlined the methodology, which included four expert interviews and an academic literature review. Section 2 served to clarify the definition of CDTs and the various interpretations that exist for this emerging area of research, which vary in terms of their levels of interactivity, data integration and interaction with the physical world. Section 3 summarized some key characteristics that enable CDTs to contribute to resilience planning, which included (1) their ability to model complexity, (2) their role in facilitating simulations and (re)imaginings of the future, and (3) their potential for supporting collaboration and community engagement processes. In section 4, the main considerations for CDT implementation were described based on current examples, both existing and under development. These considerations included (1) determining the priority hazards to be modelled based on the most pressing needs of the city in question, with the possibility of continuing to build over time, (2) identifying, collecting and managing necessary datasets, (3) developing the necessary models and facilitating their integration, and (4) improving usability for effective use of the tool by stakeholders.

Overall, the interactive nature of CDTs, their ability to depict phenomena in 3D and their capacity to integrate real-time data to inform complex simulations offers significant advantages when planning for a variety of hazards such as extreme heat, flooding, storms and air pollution. Some of the most significant challenges to implementation identified include: collecting and maintaining large amounts of data from various sources, connecting different models into one integrated platform, and ensuring usability for different stakeholders who may not be comfortable with the technology.

Considering the breadth of CDTs for urban resilience, there are many possible directions for further research, from technical and social perspectives. For instance, how might using open standards for data infrastructure might affect the interoperability between datasets from different sources? What Level of Detail (LOD) is required (or has been applied) for different urban resilience CDTs? What are some of the considerations that cities must take into account when managing big data for resilience applications?

From a social perspective, what might be the social risks of using CDTs for resilience planning, and how might CDTs further the impacts of urban threats to marginalized communities, such as gentrification, exclusion, or surveillance (K. Tynan, personal communication, 15 August, 2022)? How effective are CDT applications in enabling impactful participatory planning processes, and how can open source CDT development be made more financially feasible in the public sector (L. Mrosla, personal communication, 17 August, 2022)? Finally, how might the level of openness of a CDT (open data, open source) affect its impact on a city's resilience?

As cities consider the possibility of developing their own CDTs, it can be tempting to focus all attention on the technical capabilities of such platforms. This research has emphasized the importance of building on existing tools and social capacity that exist within the community by developing each CDT alongside stakeholders who have local expertise and lived experience of the concerned urban area. Within a resilience context, this consideration will be key in shaping effective City Digital Twins that can be adopted and integrated by the communities they serve.

References

Aydt, H. (21 October 2021). Supercomputing for Climate-informed Urban Planning. *NSCC Webinar - Preparing Singapore for Climate Change*. Retrieved 23 August 2022 from https://www.nscc.sg/wp-content/uploads/2021/10/NSCC-Webinar-Heiko-Aydt-Supercomputing-for-Climate-informed-Urban-Planning.pdf [slides] and https://www.youtube.com/watch?v=79-p-luIOXY&t=1729s&ab_channel=NSCCSingapore [video]

Aydt, H. (2020). Cooling Singapore – Towards Urban Climate Design and Management in Indicia 03, editors: S. Cairns and D. Tunas (forthcoming). Retrieved 17 August 2022 from https://www.nscc.sg/wp-content/uploads/2021/10/NSCC-Webinar-Heiko-Aydt-Supercomputing-for-Climate-informed-Urban-Planning.pdf

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Çöltekin, A. (2015). Applications of 3D City Models: State of the Art Review. *ISPRS International Journal of Geo-Information*, 4(4), 2842–2889. MDPI AG. Retrieved 21 August 2022 from http://dx.doi.org/10.3390/ijgi4042842

Connected Urban Twins. n.d. Digital twins for future urban development. Retrieved 25 August 2022 from https://connectedurbantwins.de/

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. *Sustainability*, 12(6), 2307. *MDPI AG*. Retrieved 21 August 2022 from http://dx.doi.org/10.3390/su12062307

Dembski, F., Wössner, U., & Yamu, C. (2019). Digital twin, virtual reality and space syntax: Civic engagement and decision support for smart sustainable cities. *Proceedings of the 12th International Space Syntax Symposium* Retrieved August 11 2022 from https://pure.rug.nl/ws/portalfiles/portal/90459420/2019_12SSS_Digital_Twin_Virtual_Reality_Dembski_Woessner_Yamu.pdf

Deng, T., Zhange, K., Shen, Z. M. (2021). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. *Journal of Management Science and Engineering*, 6(2), 125-134. Retrieved 22 August 2022 from https://www-sciencedirect-com.tudelft.idm.oclc.org/science/article/pii/S2096232021000238

Emprata. (n.d.). MUNICIPAL. Retrieved 31 August 2022 from https://www.emprata.com/products/municipal/

Fiware Foundation. (1 December 2020). Collaborating municipalities for disaster resiliency and sustainable growth. Retrieved 17 August 2022 from https://www.fiware.org/wp-content/uploads/FF_ImpactStories_NEC-Takamatsu.pdf

Ford, D. N. & Wolf, C.M. (2020). Smart Cities with Digital Twin Systems for Disaster Management. *Journal of Management in Engineering*, 36(4). Retrieved 17 August 2022 from https://ascelibrary-org.tudelft.idm.oclc.org/doi/full/10.1061/%28ASCE%29ME.1943-5479.0000779

Ghaith, M., Yosri, A. & El-Dakhakhni, W. (2021). Digital Twin: A City-Scale Flood Imitation Framework. *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, 250. Retrieved 21 August 2022 from https://link-springer-com.tudelft.idm.oclc.org/content/pdf/10.1007/978-981-19-1065-4.pdf

Gomez, A. & Hurtado P. (1 April 2021). Smart City Digital Twins Are a New Tool for Scenario Planning.

American Planning Association. Retrieved 25 August 2022 from https://www.planning.org/planning/2021/spring/smart-city-digital-twins-are-a-new-tool-for-scenario-planning/

Goudine, A., Newell, R., & Bone, C. (2020). Seeing Climate Change: A Framework for Understanding Visualizations for Climate Adaptation. *ISPRS International Journal of Geo-Information*, 9(11), 644. MDPI AG. Retrieved 21 August 2022 from http://dx.doi.org/10.3390/ijgi9110644

Helsinki. (2019). The Kalasatama digital twins project, the final report of the KIRA-digi pilot project. Retrieved 26 August 2022 from https://www.hel.fi/static/liitteet-2019/Kaupunginkanslia/Helsinki3D_Kalasatama_Digital_Twins.pdf

Kogut, P. (5 August 2021). Local Digital Twins: Driving Business Model Innovation in Smart Cities. *DUET*. Retrieved 25 August 2022 from https://www.digitalurbantwins.com/post/the-taxonomy-of-local-digital-twins-lessons-from-smart-cities

Ivanov, S., Nikolskaya, K., Radchenko, G., Sokolinsky, L. & Zymbler, M. (2020). Digital Twin of City: Concept Overview. *2020 Global Smart Industry Conference (GloSIC)*, 178-186. Retrieved 21 August 2022 from https://ieeexplore-ieee-org.tudelft.idm.oclc.org/document/9267879

Little, R. G., Loggins, R. A. & Wallace, W. A. 2015. Building the right tool for the job: Value of stakeholder involvement when developing decision-support technologies for emergency Management. *Natural Hazards Review*, 16(4), 05015001 https://doi.org/10.1061/(ASCE)NH.1527-6996.0000182

Open Geospatial Consortium, 2021. OGC City Geography Markup Language (CityGML) Part 1: Conceptual Model Standard. Retrieved 8 September 2022 from https://docs.ogc.org/is/20-010/20-010.html#toc0

Orozco-Messana, J., Iborra-Lucas, M., & Calabuig-Moreno, R. (2021). Neighbourhood Modelling for Urban Sustainability Assessment. *Sustainability*, 13(9), 4654. MDPI AG. Retrieved 21 August 2022 from http://dx.doi.org/10.3390/su13094654

Park, J., & Yang, B. (2020). GIS-Enabled Digital Twin System for Sustainable Evaluation of Carbon Emissions: A Case Study of Jeonju City, South Korea. Sustainability, 12(21), 9186. MDPI AG. Retrieved August 8 2022 from http://dx.doi.org/10.3390/su12219186

Petrone, J. (December 2021). Estonian and Finnish researchers unveil new applications for GreenTwins project. Research in Estonia. Retrieved 25 August from https://researchinestonia.eu/2021/12/06/estonian-and-finnish-researchers-unveil-new-applications-for-greentwins-project/

Resilient Cities Network, (n.d.). Urban Resilience. Retrieved 25 August 2022 from https://resilientcitiesnetwork.org/urban-resilience/

City of Vancouver, (2019). Resilient Vancouver. Retrieved 25 August 2022 from https://vancouver.ca/files/cov/resilient-vancouver-strategy.pdf

Schrotter, G.; Hürzeler, C. The Digital Twin of the City of Zurich for Urban Planning. Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 88, 99–112 Retrieved August 8 2022 from https://link-springer-com.tudelft.idm.oclc.org/article/10.1007/s41064-020-00092-2

Shahat, E., Hyun, C. T., & Yeom, C. (2021). City Digital Twin Potentials: A Review and Research Agenda. Sustainability, 13(6), 3386. MDPI AG. Retrieved from http://dx.doi.org/10.3390/su13063386

Truu, M., Annus, I., Roosimägi, J., Kändler, N., Vassiljev, A., & Kaur, K. (2021). Integrated Decision Support System for Pluvial Flood-Resilient Spatial Planning in Urban Areas. *Water*, 13(23), 3340. MDPI AG. Retrieved 21 August 2022 from http://dx.doi.org/10.3390/w13233340

National Research Foundation. (n.d.). About Virtual Singapore Retrieved 31 August 2022 from https://www.nrf.gov.sg/programmes/virtual-singapore/video-gallery

“Zürich virtuell” (n.d.). Retrieved 31 August 2022 from https://web.stzh.ch/appl/3d/zuerichvirtuell/

Appendices

Appendix A: Literature review search terms

Concept	Resilience	Digital Twin*	Urban Planning	Hazard*
Synonym(s)	Preparedness Sustainab* Durab* Adapt* Liveability Equity Wellbeing	Spatial decision support software Urban digital twin* City digital twin* Simulation Game-engine	Urban design Planning Design City planning Communit* Co-creation Participat*	Disaster* Climate* Earthquake* Flood* Heat* Temperature

Search query 1	"resilience" OR "preparedness" OR "sustainab*" OR "durab*" OR "adapt* OR "liveability" OR "equity" OR "wellbeing"
Search query 2	"digital twin*" OR "spatial decision support software" OR "sdss" OR "urban digital twin*" OR "city digital twin*" OR "simulation" OR "game-engine"
Search query 3	"urban planning" OR "urban design" OR "planning" OR "design" OR "city planning" OR "communit*" OR "co-creation" OR "participat*"
Search query 4	"hazard*" OR "disaster*" OR "climate*" OR "earthquake*" OR "flood*" OR "heat*" OR "drought" OR "extreme"
Search query 5	("resilience" OR "preparedness" OR "sustainab*" OR "durab*" OR "adapt* OR "liveability" OR "equity" OR "wellbeing") AND ("digital

	twin*” OR “spatial decision support software” OR “sdss” OR “urban digital twin*” OR “city digital twin*” OR “simulation” OR “game-engine”) AND (“urban planning” OR “urban design” OR “planning” OR “design” OR “city planning” OR “communit*” OR “co-creation” OR “participat*”) AND (“hazard*” OR “disaster*” OR “climate*” OR “earthquake*” OR “flood*” OR “heat*” OR “drought” OR “extreme”)

Web of Science Search

(TS=resilience OR TS=preparedness OR TS=sustainab* OR TS=durab* OR TS=adapt* OR TS=liveability OR TS=equity OR TS=wellbeing) AND (TS="digital twin*” OR TS=“spatial decision support software” OR TS=sdss OR TS=“urban digital twin*” OR TS=“city digital twin*” OR TS=“game-engine”) AND (TS=“urban planning” OR TS=“urban design” OR TS=“city planning” OR TS=“planning” OR TS=“design” OR TS=communit* OR TS=co-creation OR TS=participat*) AND (TS=hazard* OR TS=disaster* OR TS=climat* OR TS=earthquake* OR TS=flood* OR TS=heat* OR TS=drought)

SCOPUS Search

\\(TITLE-ABS-KEY(resilience) OR TITLE-ABS-KEY(preparedness) OR TITLE-ABS-KEY(sustainab*) OR TITLE-ABS-KEY(durab*) OR TITLE-ABS-KEY(adapt*) OR TITLE-ABS-KEY(liveability) OR TITLE-ABS-KEY(equity) OR TITLE-ABS-KEY(wellbeing)) AND (TITLE-ABS-KEY("digital twin*”) OR TITLE-ABS-KEY(“spatial decision support software”) OR TITLE-ABS-KEY(sdss) OR TITLE-ABS-KEY(“urban digital twin*”) OR TITLE-ABS-KEY(“city digital twin*”) OR TITLE-ABS-KEY(“game-engine”)) AND (TITLE-ABS-KEY(“urban planning”) OR TITLE-ABS-KEY(“urban design”) OR TITLE-ABS-KEY(“city planning”) OR TITLE-ABS-KEY(“planning”) OR TITLE-ABS-KEY(“design”) OR TITLE-ABS-KEY(communit*) OR TITLE-ABS-KEY(co-creation) OR TITLE-ABS-KEY(participat*)) AND (TITLE-ABS-KEY(hazard*) OR TITLE-ABS-KEY(disaster*) OR TITLE-ABS-KEY(climat*) OR TITLE-ABS-KEY(earthquake*) OR TITLE-ABS-KEY(flood*) OR TITLE-ABS-KEY(heat*) OR TITLE-ABS-KEY(drought))

Appendix B: Interview Questions

The following guiding questions were shared with interviewees prior to each meeting.

Research Project:
Digital Twins and Spatial Decision Support Software for Urban Resilience
Adele Therias
August 2022

Expert Interview Questions
Note: All questions are concerned with the use of Digital Twins and Spatial Decision Support Systems focused on urban resilience (in particular: disaster response, climate change adaptation, liveability and/or equity).

Background and Context
- What is your current role in relation to the topic of Digital Twins and/or Spatial Decision Support Systems?
- What is your experience working with, developing and/or facilitating the use of DTs/SDSSs?

Societal needs and potential
- In what way(s) have you come across DTs/SDSS being used for urban resilience topics?
  - What were some of the impacts that you observed as a result of these tools?
  - What were some of the limitations that you observed in the use of these tools?
- In what way(s) have you come across DTs/SDSS being used to engage interdisciplinary teams (experts) in planning / response processes?
- In what way(s) have you come across DTs/SDSS being used to engage community members in co-creating solutions / participatory processes?

Technical needs and potential:
- What are some of the most commonly used DT/SDSS platforms and softwares that you use/are used in your field?
- Have you come across and/or used open (non-proprietary) software(s) and platforms for DTs/SDSSs?
  - How accessible, usable and effective were they?
- What are some key technical developments that you have observed in the effectiveness, accessibility and usability of DTs/SDSS in recent years?
- What are the biggest technical limitations that you have observed in the use of DTs/SDSSs?
  - E.g. How does the simulation performance (speed, etc) impact the efficiency and convergence of co-creation and participatory processes?
  - E.g. How does the level of interactivity of Digital Twin/SDSS impact the community member engagement and participatory planning?

Conclusion
- Any additional comments?
- Any resources and/or contacts you would recommend for further research on this topic?

Appendix C: Summary of CDTs

Project Name and Link	**Location(s)**	**Resilience topic(s)**	**Phenomena modelled**	**Data**	**Interactivity**	**Software**	**Open source**
*Connected Urban Twins (CUT)**	*Hamburg, Munich, Leipzip (Germany)*	*Energy, climate and future-proof infrastructure and area planning, citizen participation*	*TBD*	*For Hamburg, based on urban data hub and the corresponding urban data platform.*	*Participation module, VR module, "build your own twin" module, storytelling*	*Masterportal, Cesium, Open Layers*	Yes
*Digital Urban Climate Twin (DUCT)**	*Singapore*	*Urban Heat Island*	*Land-use, industry, power plants, traffic, building energy model, urban climate*	*Electricity demand, anthropogenic heat, vegetation, urban geometry / properties, meteorological data, climatic boundary conditions*	*Web service*	*Simulation as a Service (SaaS middleware)*	No
Kalasatama digital twins project	Helsinki (Finland)	Renewable energy, wellbeing	Wind speed and direction, solar hour analysis, sun shadow	Aerial photography, Buildings and infrastructure (CityGML), terrain	Gaming platform, AR, VR, model construction projects	Unity online streaming service (Umbra Composit™), OpenCities Planner	No
A City-Scale Flood Imitation Framework	Calgary (Canada)	Flooding	Water infrastructure, power infrastructure, transportation infrastructure	City information model built from open street maps, DEM, satellite imagery, flow records, historical flood extents	Unknown	Hec-Ras (simulates floods in 2D + 3D), GIS	No
*Digital Twin Victoria**	*Melbourne (Australia)*	*Bushfire and emergency response, canopy*	*Unknown*	*3D Buildings, vegetation, elevation*	*Unknown*	*Cesium, TerraJS*	*Yes*

		cover		*(LiDAR)*			
Extreme Weather Layer	Haapsalu (Estonia) and Söderhamn (Sweden)	Flooding, climate change	Land developments, urban drainage systems, hydraulic modelling, EPA Storm Water Management Model	Storm water system, climate prediction and adaptation plans, urban plans, cadastral info, land cover, DEMs, land use, topography, soil type, rainfall	Non-expert visualization and further analysis in GIS	Unknown	No
Zürich virtuell	Zurich (Switzerland)	Noise pollution, air pollution, mobile phone radiation, solar potential, flooding, urban climate	Micro and meso-scale climate models	Digital Terrain Model, 3D buildings, 3D roofs, trees	Visualization of new designs, pedestrian mode, building mode, split screen	Unknown	No
Multi-network interdependent critical infrastructure program for the analysis of lifelines (MUNICIPAL)	North Carolina (USA)	Extreme weather recovery, infrastructure recovery	HAZUS-MH, wind speeds, flood levels	Hurricane data, infrastructure (power, water, wastewater, communications, transportation), critical facilities (hospitals, airports, and nursing homes)	vulnerability simulator, restoration solver, GIS interface	Unknown	Yes
Takamatsu City's Disaster Management Solution	Takamatsu (Japan)	Flooding	Flood risk, shelter conditions	humidity sensors, electricity consumption, water level sensors, weather forecast, road network	Dashboard for real-time monitoring, dispatch of human resources	FIWARE IoT platform (Generic Enablers = Orion Context Broker, STH-Comet, Cignus)	Yes

Herrenberg Digital Twin	*Herrenberg (Germany)*	*Air pollution, public space*	*Urban mobility/traffic simulation (SUMO), Air flow simulation (OpenFOAM)*	*Volunteered Geographic Information, Street network, buildings*	*AR, VR*	*OpenCOVER (render), CoVISE (visualization)*	*Yes*
*NSW Spatial Digital Twin**	*New South Wales (Australia)*	*Bushfires*	*Unknown*	*telecommunications and utility infrastructure, Government Radio Network (GRN) telecommunications towers and assets*	*Community Engagement*	*TerriaJS, Magda, Cesium, Leaflet*	*Yes*
GIS-Enabled Digital Twin System for Sustainable Evaluation of Carbon Emissions	Jeonju (South Korea)	Carbon emissions	Determine factors influencing carbon emissions, Hot spot analysis of carbon emissions	Electricity, gas waste, vehicles, 3D buildings	Unknown	Unknown	No

**Under development*