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City digital twins for urban resilience

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ABSTRACT

With increased urbanization and the impacts of climate change, cities around the world are making resilience-building a priority. Simultaneously, advances in technology have enabled the creation of City Digital Twins (CDTs). Informed by a literature review and interviews with resilience and Digital Twin experts, this paper explores how CDTs might support the development of more resilient urban communities. First, the various definitions of urban resilience, smart cities and CDTs are described. Second, the paper explores how characteristics of CDTs make them uniquely equipped to facilitate (1) a better understanding of complex phenomena, (2) the imagination of possible futures and (3) collaboration between stakeholders. Finally, the technical requirements and challenges of CDT implementation are discussed, including (1) identifying priority hazards and users, (2) collecting and managing data, (3) integrating different models and (4) ensuring usability. The paper concludes by emphasizing the important role of stakeholders in shaping CDTs that can be successfully integrated by the communities they serve.

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KEYWORDS
City digital twin; resilience; hazard; collaborative

1. Introduction

With the exponential growth of cities and the impacts of climate change, urban areas 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 (Lopez, Leonardo, and Grijalba Castro 2021). 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, Zhang, and Shen 2021).

One such challenge is the threat of hydro-meteorological events (Lopez, Leonardo, and Grijalba Castro 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 occurred, Takamatsu City has developed a comprehensive visualization and prediction system to inform its disaster management practices and enable proactive interventions such as pre-emptive evacuation of vulnerable areas. As shown in Figure 1, the platform draws from 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.

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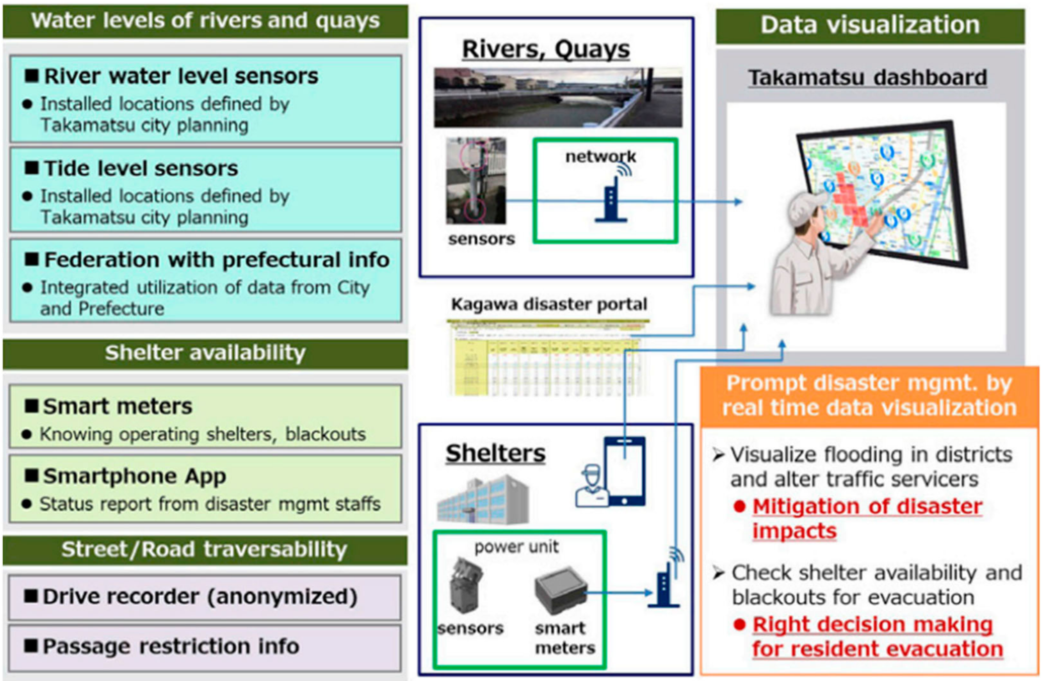

Figure 1. Takamatsu city's disaster management solution (Fiware Foundation 2020).

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. In response to the 2004 typhoon, the local government invested in such a digital twin to build its resilience towards future disasters, and many other local, regional and national governments have allocated resources for the development of similar toolsBy highlighting some key trends and questions at the intersection of urban resilience and digital twins, this paper examines the question: how might City Digital Twins (CDTs) support the development of more resilient urban communities? The research sub-questions include:

(1) To what extent have CDTs been used for resilience planning?
(2) How might unique functionalities and characteristics of CDTs address gaps in planning for, and responding to, natural disasters?
(3) Which technical developments influence the effectiveness, accessibility and usability of CDTs?
(4) What are some best practices and risks regarding CDT implementation?

The objective of this paper in addressing the questions above is to help inform innovative and effective resilience-building processes and tools. In section 2, the methodology and research framework are described. Section 3 provides an overview of key concepts explored in this research, including urban resilience, smart cities and digital twins. Findings related to the various ways in which CDTs may be relevant to resilience planning (sub-questions 1 and 2) are outlined in Section 4. Section 5 focuses on findings relating to the technical requirements, benefits and challenges of CDT implementation (sub-questions 3 and 4).

2. Methodology and framework

This research uses Grounded Theory ("Grounded Theory," 2023) as its methodological framework to carry out a review of the use of City Digital Twins (CDTs) for urban resilience based on a literature review and expert interviews. As depicted in Figure 2, this approach is non-linear and involves an iterative cyclical process of (a) collecting data, (b) identifying concepts from the data, (c) grouping concepts into categories and (d) identifying relationships between categories, which inform further data collection. This cyclical process is carried out three times: the first cycle involves case studies, theory, and analytical data from the literature review. These initial findings inform the foundation of the research and the development of the interview questions. The second cycle is focused on the data collected during interviews and also helps to identify additional literature and concepts to explore. A final cycle returns to the literature to deepen the analysis of the previous two cycles. Within each cycle, the data collection and analysis cover four topic areas ranging from the broadest to the most specific: defining urban resilience, defining City Digital Twins, the use of CDTs for urban resilience, and the technical implementation of CDTs for urban resilience. The findings in the fourth step of the cycle (relationships between categories) are considered the results of the research and are described in detail, combining observations from the three cycles, therefore drawing connections between the findings from the interviews and literature review.

The literature review was carried out 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 (see Appendix A) and used to write search queries adapted to two specific platforms: Scopus and Web of Science. The initial systematic searches were restricted to the last five years in order to focus on the most recent technological innovations and were filtered to academic articles only. The resulting articles were screened for the following criteria:

- Relevance to the research topic (e.g. excluding literature on digital twins of machinery and other products that do not correspond to the urban scale)

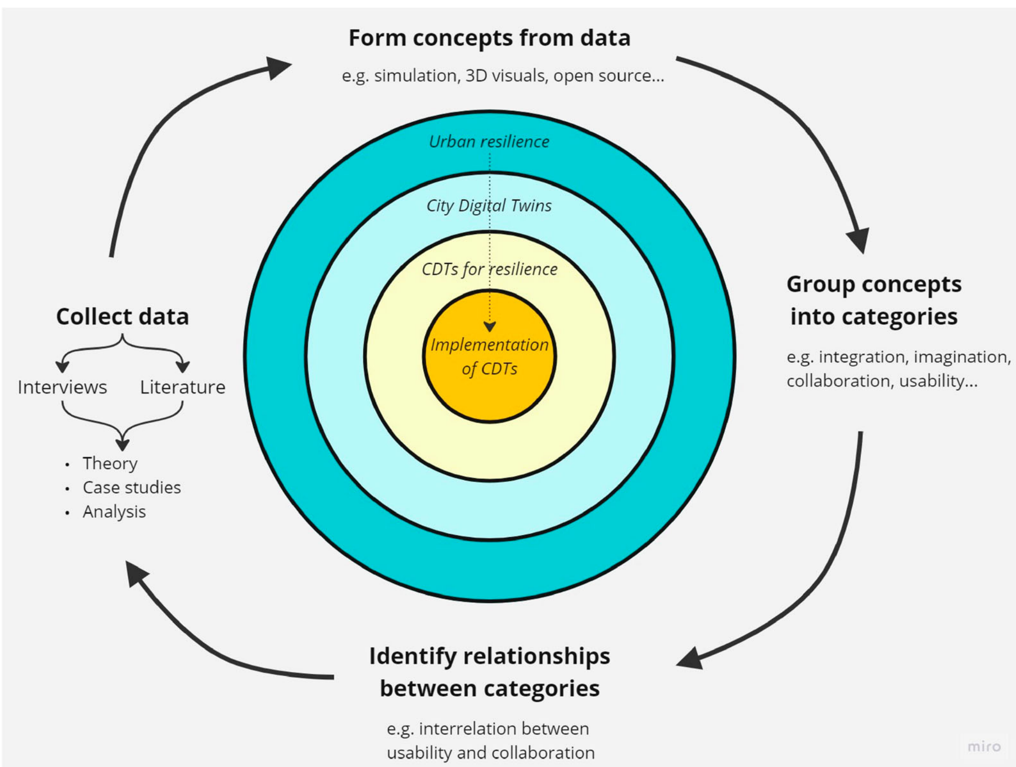

Figure 2. Research framework based on grounded theory. Adapted from "Grounded Theory," 2023).

- Peer-reviewed academic articles
- English language

From this initial list of literature, additional sources were identified based on the reference list from each article in a snowball fashion.

Semi-structured expert interviews were carried out with researchers and practitioners in the field (s) of resilience and/or CDTs. An open call for interviewees was publicly posted on LinkedIn in August 2022 and individuals contacted the authors directly or were recommended by colleagues. As depicted in Figure 3, the experts interviewed for this research included academic researchers and practitioners in the fields of urban resilience. Several of the interviewees worked at the intersection of CDTs and urban resilience from academic and industry perspectives, enabling them to share insight into the theoretical and aspirational concepts related to CDTs, as well as the reality and complexity of development and implementation. Each of these CDT experts had a specialization related to (a) key infrastructure, (b) vegetation modelling or (c) municipal CDT implementation. In addition, one interviewee worked on resilience planning at the local government level and could comment on the nature of this work and the potential for a CDT to support it. 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. 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. Specific findings informed by the interviews have been cited as 'personal communication.'

3. Key concepts and definitions

3.1. Urban resilience

The concept of 'urban resilience' is one with many interpretations and a lacking common definition (Amirzadeh, Sobhaninia, and Sharifi 2022; Feldmeyer et al. 2019; Nguyen and Akerkar 2020; Roy,

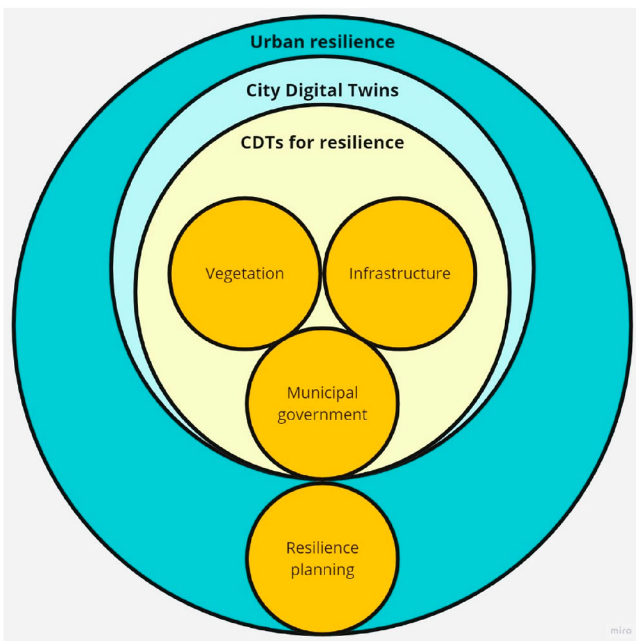

Figure 3. Specializations included in expert interviews.

Siddika, and Sresto 2021). The discrepancies in interpretation can be attributed to the linguistic origin of the word 'resilience,' the evolution of the term in different disciplines, and the different conceptual models employed in its usage (Amirzadeh, Sobhaninia, and Sharifi 2022). While the latin origin of the word refers to 'bouncing back,' the word has also been used to refer to communities' ability to adapt to unexpected changes, and even 'bounce forward' (Feldmeyer et al. 2019). Furthermore, the term is used in many different scientific fields, such as ecology, psychology, and economy, and each field applies its own meaning and connotations (Amirzadeh, Sobhaninia, and Sharifi 2022).

Importantly, the chosen definition of urban resilience has an impact on the formulation of objectives and interventions when carrying out resilience planning. Two major conceptual approaches to resilience are the 'equilibrium model,' which involves the capacity of systems to return to original state following a disturbance, and the 'non-equilibrium' model, which understands the need for systems to change in response to changing circumstances. While the former can lead to inadequate responses that do not prepare a system for further potential changes and risks, the latter aims to establish a new 'sustainable state,' and focuses on adaptiveness rather than reducing vulnerabilities (Amirzadeh, Sobhaninia, and Sharifi 2022). A third approach, which is a hybrid of the two, 'addresses the co-occurrence of the capacities for "bounce back" and "bounce forward"' (Folke 2016 as cited in Feldmeyer et al. 2019).

Furthermore, numerous pressures threaten the stability of urban systems, including geological (e.g. volcanism), hydro-meteorological (e.g. cyclones), sanitary-ecological (e.g. pandemics) and socio-organizational (e.g. terrorism) (Lopez, Leonardo, and Grijalba Castro 2021). These events may interact with each other, creating unique circumstances in each city which generate particular resilience planning needs. While some approaches to resilience focus on general resilience of a city to any possible threat, considering the overall system characteristics, other approaches emphasize specific resilience to isolated threats (Amirzadeh, Sobhaninia, and Sharifi 2022). While some scholars believe we cannot separate resilience planning for different threats and must take an integrated and holistic approach, others believe we can only work on resilience to specific phenomena for actions to become concrete (Amirzadeh, Sobhaninia, and Sharifi 2022).

It is important to note that urban resilience is influenced by many interacting components. The framework shown in Figure 4 includes 'systems' ('settlements, infrastructure, and ecosystems'), 'agents' ('individuals, households, communities, political actors, and organizations'), and 'institutions' ('policies, laws, social norms'), all of which play key roles and interact with each other to build resilience (Tyler and Moench (2012) as cited in (Amirzadeh, Sobhaninia, and Sharifi 2022)). Similarly, practitioners in the Resilient Cities Network define urban resilience 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.).

The numerous components of, and threats to, urban systems make it challenging to track and measure the effectiveness of resilience initiatives, therefore indicators play an important role to guide practitioners and measure the impact of actions (Feldmeyer et al. 2019). Yet, the establishment of such indicators is not straightforward due to varying definitions and context-specific factors (Feldmeyer et al. 2019): '[t]he concept of urban resilience is dynamic and suggests numerous pathways' (Roy, Siddika, and Sresto 2021). Many existing methodologies aim to determine the level of resiliency of various systems in a quantitative way, such as the 'Baseline Resilience Indicators for Communities (BRIC),' the 'Climate Disaster Resilience Index (CDRI),' and the 'Simpsons Community Resilience Index' (Roy, Siddika, and Sresto 2021), all of which involve scoring various characteristics and comparing scores between locations. However, research on the perceived relevance of different indicators across cities in Germany shows that some indicators are considered more relevant than others (Feldmeyer et al. 2019). For example, the top 5 indicators in the study were found to be: the presence of cold air parcels; inter-offices working groups regarding risk, climate change and resilience; strategies against heavy rain and heat in plans; experience with extreme events in the

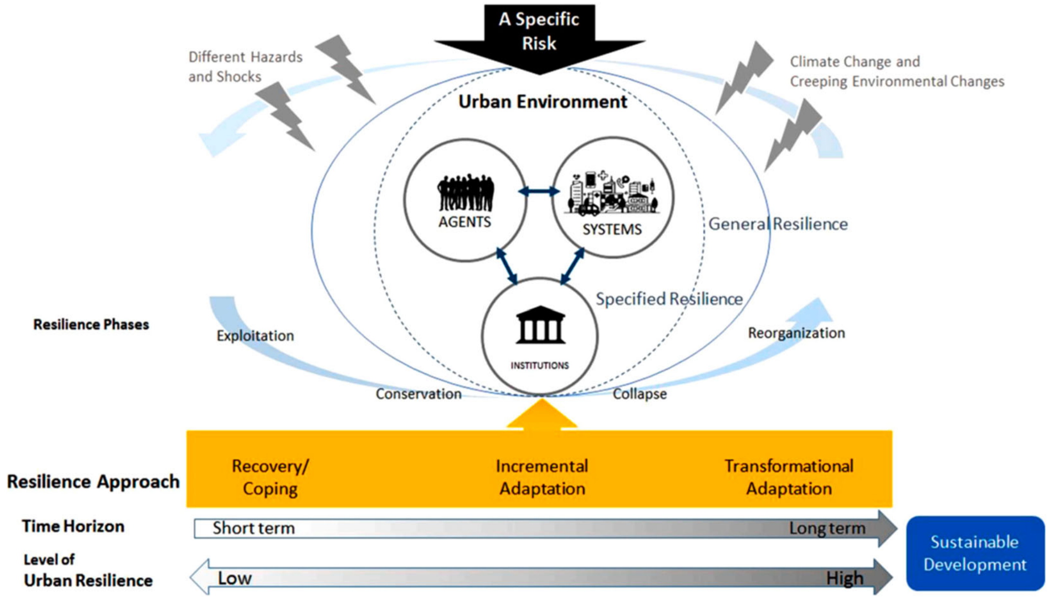

Figure 4. The conceptual framework of urban resilience- adapted from Torabi, Dedekorkut-Howes, and Howes (2018) (as cited in Amirzadeh, Sobhaninia, and Sharifi 2022).

last five years; and citizen information about heat, heavy rains and flooding (Feldmeyer et al. 2019). Furthermore, the relevance of different indicators is context-specific and some of the indicators that would be relevant to developing countries were excluded from the study due to their irrelevance to Germany, such as rates of literacy (Feldmeyer et al. 2019). As a result, qualitative approaches to evaluating resilience also play an important role in generating an understanding of a community (Nguyen and Akerkar 2020). One example of a qualitative approach is the 'Community Resilience System (CRS)' which involves six stages described in Figure 5: 'engagement, assessment, visioning, planning, implementing, and monitoring and maintaining' (Nguyen and Akerkar 2020). Each stage plays an important role, and the quality of each stage has a subsequent effect on the community's resilience.

In this paper, the term 'urban resilience' refers to an urban system's adaptive capacity in the general sense, and specific resilience to threats such as natural hazards and climate impacts. The definition used considers the roles of, and interconnections between, different actors as conceptualized by Torabi, Dedekorkut-Howes, and Howes (2018) (as cited in Amirzadeh, Sobhaninia, and Sharifi 2022). The scope of this research does not enable the precise quantification of CDT impacts on urban resilience in specific contexts. However, the value of CDTs is observed in terms of their potential contribution to, or enhancement of, the qualitative stages of the Community Resilience System (CRS) (Nguyen and Akerkar 2020) described above.

3.2. Smart city

The governance and administration of growing cities is increasingly complex (Lopez, Leonardo, and Grijalba Castro 2021). Simultaneously, urban areas are becoming smarter with the development of ICT, machine learning and data mining, leading to the evolution of the 'Smart City' (White et al. 2021). The term 'Smart City' has many definitions, but researchers agree that it involves the following dimensions: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance (Sikora-Fernandéz 2017 as cited in Lopez, Leonardo, and Grijalba Castro 2021). A smart city's infrastructure enables the collection and processing of data for the benefit of government entities

1. Engagement	Seek for resilience champions, organise them into a logical and consistent leadership team, and build well-established and trusted community networks
2. Assessment	Derive self awareness by comprehending its interdependencies and vulnerabilities, categorise its accessible resources, and discover which resources are at risk
3. Visioning	Give a summary of the importance of possessing a resilience-focused vision and explain how community can include resilience into an existing vision or generate a new vision
4. Planning	Link present state of community and determine a series of activities that are particular, assessable, and supportive of improved daily community function
5. Implementing	Ensure an organisational home for community resilience program either through establishing a new organisational entity or by integrating into existing public or private organisations
6. Monitoring and maintenance	Monitor and assess the progress of individual projects and entire community resilience program, making adjustments and alterations as required

Figure 5. Community Resilience System (CRS) stages (adapted from Nguyen and Akerkar 2020).

(Lopez, Leonardo, and Grijalba Castro 2021), informing the management of everyday ‘mobility, environment, living standards and governance of the city’ (White et al. 2021). Sources of data collection are varied and dependent on the infrastructure of each locale, ranging from traditional surveillance methods such as CCTV cameras, to individual devices such as mobile phones, smart watches, and vehicles, to environmental sensors such as smart trees (e.g. with moisture sensors at the roots), fire sensors, and wind sensors (White et al. 2021).

Beyond the everyday, smart cities are viewed as a promising solution to the numerous risks faced by urban systems and important contributors to improved resilience, considering their emphasis on monitoring and data-driven planning (Zhu, Dezhi, and Feng 2019). In particular, the large amount of highly diverse data that they gather, process, and analyze are relevant to infrastructural systems, which can significantly speed up a city’s recovery from disasters (Zhu, Dezhi, and Feng 2019). A statistical analysis of resilience and smart city factors in China indicates that smartness has a positive influence on resilience, particularly on institutional, economic and infrastructural resilience in well-established smart cities (Zhu, Dezhi, and Feng 2019). However, the correlation with social resilience is less significant: for instance, the efficient top-down management of disaster response can have a negative impact on the population’s ability to prepare for, and respond to, unexpected crises, subsequently reducing the social resilience (Zhu, Dezhi, and Feng 2019). Therefore, the unique characteristics and governance model of each smart city are important factors in its resilience. Furthermore, the amount and quality of real-time data and analytics in a smart city can enable the creation of its digital twin, and potentially enable the modelling of planning and policy decisions (White et al. 2021) as will be discussed in the following section.

3.3. City digital twin (CDT)

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 and Hürzeler 2020), ‘Urban Digital Twin’ (Dembski et al. 2020), ‘Local Digital Twin’ (Kogut 2021) and ‘City Digital Twin’ (Shahat, Hyun, and Yeom 2021), the last of 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 to simulate the object's physical responses to external conditions and improve the design prior to building physical prototypes (Deng, Zhang, and Shen 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, Hyun, and Yeom 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'. 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.

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 et al. 2020) 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). The CDT acts as a container and connector for these different digital twins, aiming to model the urban environment as a whole (Dembski, Yamu, and Wössner 2019). 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.

CDTs have a vast range of potential uses, as shown in Figure 6. Beyond focusing on visualizations, many definitions of the CDT emphasize their role in presenting current situation and predicting future conditions in a way thats boost decision-making (Ford and Wolf 2020). Park and Yang (2020) assert that the virtual environment must have a complex mechanism for planning, simulating, assessing, and monitoring the physical world 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'.

Some researchers take this one step further, stating that a true CDT must also involve the digital realm exerting influence on the physical world, such as through automated data-driven responses to situations (Shahat, Hyun, and Yeom 2021). Based on this definition, some experts in the field explain that the current platforms should for the most part be referred to as 'Digital Shadows.' The following definition is used in this paper: a CDT is the bi-directional 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.

4. Results

This section outlines the findings resulting from the literature review and expert interviews carried out in this research following the research framework defined in section 2, in the context of the Community Resilience System (CRS) framework presented in section 3.1 (Nguyen and Akerkar 2020). As shown in Table 1, 27 key concepts were identified. These concepts were grouped into 13 categories, and 6 relationships between categories were observed and described. The findings presented in this section are informed by an examination of the relationships between identified categories. Section 4.1 outlines the findings addressing sub-questions (1) *To what extent have CDTs been used for resilience planning?* And (2) *How might unique functionalities and characteristics of CDTs address gaps in planning for, and responding to, natural disasters?* Section 4.2 outlines the findings addressing sub-questions (3) *Which technical developments influence the effectiveness,*

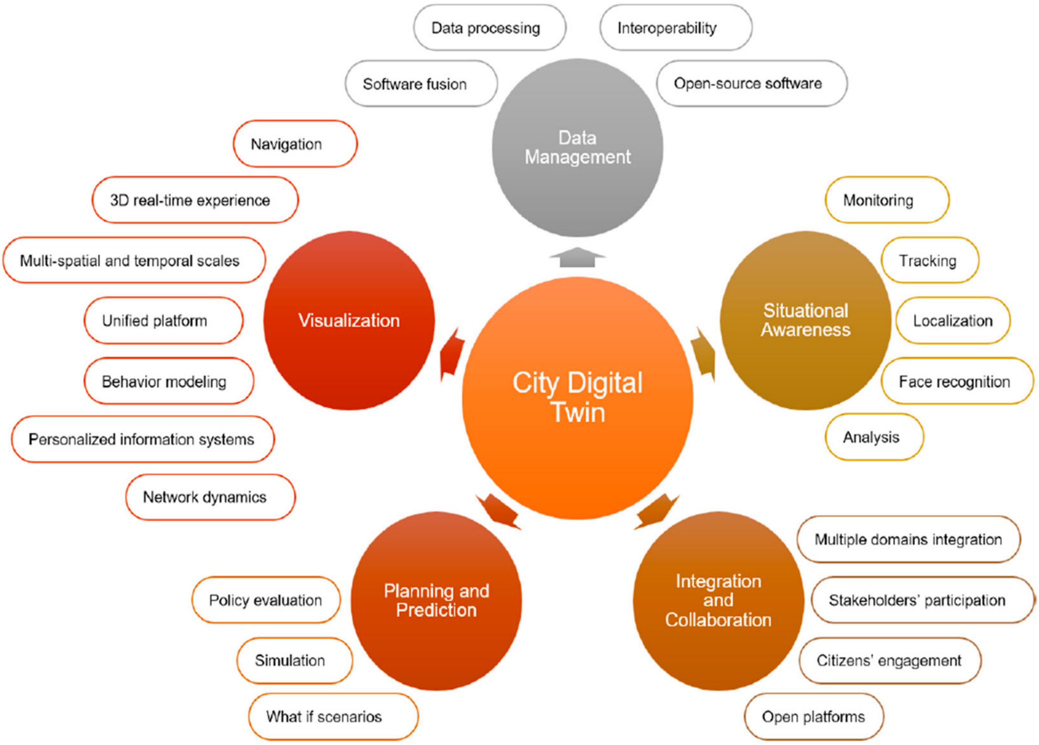

Figure 6. City digital twin potentials (Shahat, Hyun, and Yeom 2021).

accessibility and usability of CDTs? And (4) *What are some best practices and risks regarding CDT implementation?*

4.1. CDTs for urban resilience

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? 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 (Katia Tynan, personal communication, 15 August 2022). The findings from this research, elaborated below, indicate that CDTs can support resilience-building by enabling an improved understanding of complexity, facilitating the imagining of possible future(s) and supporting stakeholders in (re)acting together to various urban challenges.

4.1.1. Comprehending complexity

Ford and 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.' Yet, they note that many existing disaster management models do not

Table 1. Results following Grounded Theory framework.

Identified concepts	Categories	Relationships	Findings	Theme
3D Disaster Emergency Response Visualization Stakeholder Governance Prediction Practice	Simulation Complexity Imagination Education Decision-making Collaboration Real-time analysis	*Simulations* enable understanding of *Complexity* *Simulations* facilitate *Education* through *Imagination* of scenarios *Real-time analysis* and *Simulation* enable practice and real-time *Collaboration* and *Decision-making*	Comprehending complexity Imagining possible future(s) (Re)acting together	CDT for urban resilience
Vegetation Computation Climate Visualization Real-time Data collection Transparency Open source Tech / data literacy Engagement Unification Tech challenge, improvement Scale AR/VR Infrastructure Privacy Experimentation Structure Stewardship	Community Usability Integration Prioritization Interoperability Model Data	*Community* context must be considered for *Prioritization* of hazards and users The usability of *Data* relies on the *Integration* of various sources and *Models* *Interoperability* of *Models* enables *Integration* of different phenomena Designing with *Community* in mind shapes tool *Usability*	Setting priorities: hazards and users Data collection and management Integrating models Ensuring usability	Implementation of CDT

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, and El-Dakhakhni 2021). Ghaith, Yosri, and El-Dakhakhni (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 7. The ability of CDTs to enable deeper understandings of complex phenomena aligns with the 'Assessment' stage of the Community Resilience System (CRS) framework, which describes the ability of a city to understand its interdependencies and vulnerabilities, identify its assets and potential risks (Nguyen and Akerkar 2020).

One example is the GreenTwins project: a research collaboration that involved 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 usually missing from CDTs, even though it can play a key role in hazards such as flooding, microclimate, urban biodiversity and air quality (Laura Mrosla, personal communication, 17 August 2022). This is in part because vegetation is very complex to model, and one of the outcomes of GreenTwins was a plant library containing algorithmically modelled plants that can be implemented into a CDT.

Considering that disaster management involves the collaboration of stakeholders who may not otherwise work together, a CDT could deepen actors' understanding of the complexity and interdependencies of disaster events, and the work that is needed to restore crucial infrastructure

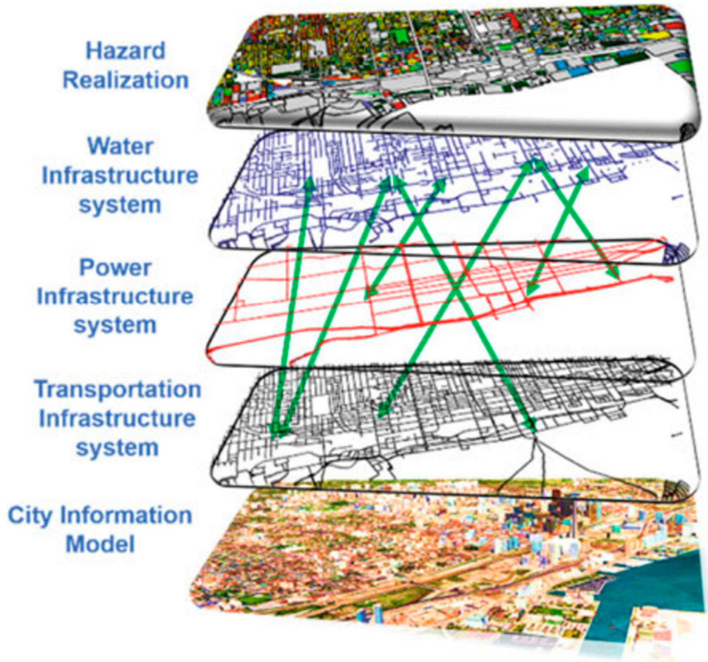

Figure 7. Modelling the complexity of flooding in a CDT (Ghaith, Yosri, and El-Dakhakhni 2021).

(Little, Loggins, and Wallace 2015). For example, the City of Vancouver previously 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 centres 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. This potential for facilitating collaboration aligns CDTs with the 'Engagement' and 'Planning' stage of the Community Resilience System (CRS) framework, which respectively emphasize the establishment of collaboration networks, and determine the activities necessary to ensure the continued function of the community (Nguyen and Akerkar 2020).

The complexity that makes CDTs such a rich tool is simultaneously one of the most challenging aspects of their implementation. 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, and 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?

4.1.2. Imagining possible future(s)

A key capability of City Digital Twins (CDTs) which goes beyond the understanding of the current situation, is 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 (Ford and Wolf 2020). 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 and Hürzeler 2020). There are also larger scale complex simulations as described in the following example:

The Extreme Weather Layer, which combines the urban drainage system (UDS) digital twin with the GIS system, intends to support city governments in analysing the impact of climate change and new developments, as well as the simultaneous flooding risk, at both a single plot and at the urban scale, on the existing infrastructure (Truu et al. 2021). Once the data (e.g. on UDS, rainfall, land use and topography) are known, the hydraulic modelling software can be applied for determining the manholes in the urban area which are vulnerable to intense rainfall and the consequent flooding on the streets (2021).

The availability of such simulations can support urban planners, who must consider 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, Zhang, and Shen 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 and Yang 2020).

As shown in Figure 8, 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.

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, and Bone 2020). 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. The simulation and visualization strengths of CDTs enables them to contribute to the 'Visioning' stage of the Community Resilience System (CRS) framework in innovative, engaging and effective ways, facilitating the generation of resilience-focused visions of a community (Nguyen and Akerkar 2020).

4.1.3. (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-

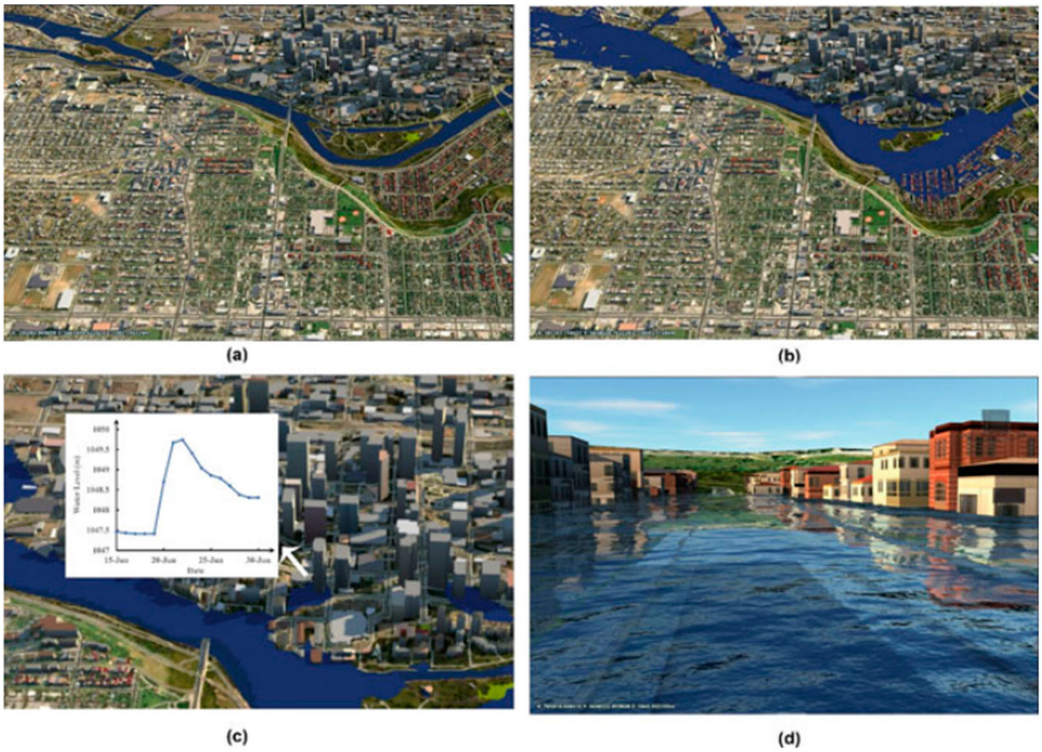

Figure 8. Calgary CDT flood simulation including bird-eye view before flood (a), bird-eye view on June 23rd (b), hydrograph at one of the buildings (c) and human-eye view of the flooded buildings (d) (Ghaith, Yosri, and El-Dakhakhni 2021).

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 they 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.

The immersive, realistic and interactive aspects of CDTs can enhance such community engagement processes in active and meaningful ways (Schrotter and 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 and 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, Yamu, and Wössner 2019). 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 (2019).

Beyond long-term resilience planning, CDTs are relevant to real-time response to disasters. For instance, 3D geospatial data can be used in disaster management and emergency response as they can provide essential information. For example, 3D city models can be used in defining the best location for the of the ladder trucks before the arrival of firefighters at the scene (Biljecki et al. 2015). This 3D real-time data is crucial for saving lives, and 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, 10 August 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 (Little, Loggins, and Wallace 2015). The decision support systems for long-term and/or real-time planning embedded in CDTs enable them to satisfy the last three stages of the Community Resilience System (CRS) framework (Nguyen and Akerkar 2020). CDTs facilitate 'Planning' by examining the impact of decisions on the current state of the community, 'Implementing' by enabling real-time responses to disasters and connecting the actions taken in the CDT to reality in the physical city, and 'Monitoring and maintenance' by ensuring ongoing tracking of the urban system characteristics through continuous data collection that can inform interventions (Nguyen and Akerkar 2020).

Overall, the value of CDT for disaster management becomes significant, as it combines 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 acts as a tool to facilitate interdisciplinary and cross-stakeholder decision-making in the short- and long-term (Ford and Wolf 2020). This combination of functions enables CDTs to contribute to all six stages of the Community Resilience System (CRS) framework, indicating that they have the potential to enhance urban resilience in a qualitative way (Nguyen and Akerkar 2020). In addition to these benefits, Ford and Wolf (2020) state that CDT for

Figure 9. VR interaction with the Herremberg CDT. Particulate matter and wind flow simulation visualized in CAVE (Dembski et al. 2020).

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.

4.2. Implementing a CDT for resilience planning

In the previous section, the potential for City Digital Twins (CDTs) to support urban resilience was explored. With many CDT developments underway and municipalities considering investing resources into their own CDT, what are some considerations to keep in mind to improve the success of a project? In this section, the paper presents key considerations that inform the technical implementation of a CDT based on examples of CDT research and development. The findings from the research indicate that the key considerations in implementing a CDT for urban resilience are setting priorities regarding hazards and users, collecting and managing data, integrating models, and ensuring usability.

4.2.1. Setting priorities: hazards and users

The first step in a CDT development is conducting research and making decisions that shape the priorities of the platform. With many potential platforms, data sources and models available, the key challenge is transforming chaotic input into one useful tool (M. Zhu, personal communication, 10 August 2022). The Connected Urban Twins (CUT) project is 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.). The first step of the project was to better understand the needs and potential for integrating different modelling efforts into a future CDT, before focusing on its development. As the lead of modelling and simulation, Rico Herzog conducted a survey to determine which departments of the Hamburg municipality were already using models (Rico Herzog, personal communication, 9 August 2022).

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, Yosri, and El-Dakhakhni 2021). Some examples of thematic CDTs include Singapore's emphasis on the urban heat island effect (Aydt 2021), Tallinn and Helsinki's research on modelling green infrastructure (L. Mrosla, personal communication, 17 August 2022), modelling carbon emissions in Jeonju (Park and Yang 2020), and preparing for flooding in Calgary (Ghaith, Yosri, and El-Dakhakhni 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'. One important aspect of people-centred technology is ensuring that stakeholders can meaningfully engage with the CDT. In North Carolina, USA, an interdisciplinary team of researchers developed MUNICIPAL, a tool for predicting damage to infrastructure elements for a specified storm event (see Figure 10). This tool produces an optimal restoration plan based on critical services and their interdependencies, and displays the outcomes through a geographic information systems (GIS) interface (Little, Loggins, and Wallace 2015). MUNICIPAL combines digital twins of relevant urban systems to support decision-making for recovery from hurricanes, and 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, Loggins, and Wallace 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 municipal employees 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 and Yang 2020) to ensure that users understand the data and results that they are using.

According to Schrotter and 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, Blindflug Studios AG developed the free game '(re)format Z:' which explores the Reformation in Zurich in a 'dystopian cyberpunk version of the city'. 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 (R. Herzog, personal communication, 9 August 2022).

4.2.2. 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, Yosri, and El-Dakhakhni 2021). 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 simulations 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

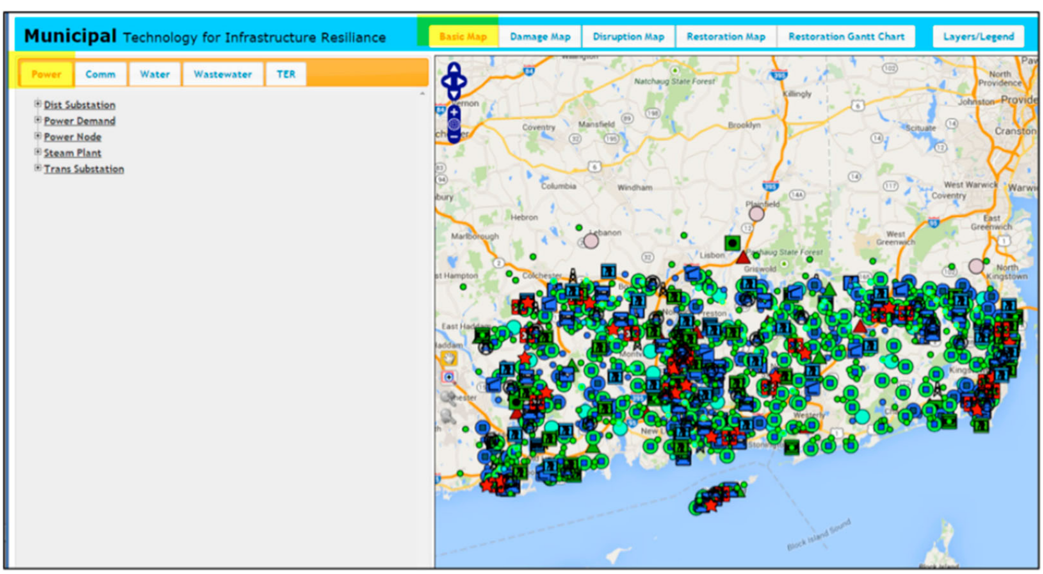

Figure 10. MUNICIPAL (Emprata n.d.).

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, however the processing of such a large dataset was extremely computationally intensive and the neighbourhood was divided into tiles to model smaller subsets at one time.

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 considered 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. BIM and GIS models overlap with city information modelling, but with different scopes. While the focus of BIM lies on very rich semantic and detailed information modelling at the building and construction scale, GIS data describes environmental [spatial] and temporal information, which is less detailed but possibly with higher update frequency (Helsinki 2019).

The question of how to successfully integrate BIM into a City Information Model has been posed many times in CDT research (e.g. Biljecki et al. 2015; Park and Yang 2020; Schrotter and Hürzeler 2020). 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.

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 11). In some cities, building this foundation for the CDT is a significant barrier. 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 (K. Tynan, personal communication, 15 August 2022).

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, 10 August 2022). In the most dynamic version of the CDT concept, the platform can receive and efficiently process data flows which are automatically collected through distributed 'Internet of Things' (IoT) sensor systems. The Digital Twin of the city is progressively filled with the data of the real city, which is gathered in real-time from deployed IoT infrastructure and urban information systems as shown in Figure 12 (Ivanov et al. 2020). 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 the updates which are of lower frequency, such as history/evolution of cities (e.g. building construction/demolition) as well as the management of multiple versions of the city models. The Dynamizer module manages higher frequency/dynamic variations of object properties, such as variations of thematic attributes (e.g. physical quantities includingenergy demands, temperature, solar irradiation levels), spatial properties (e.g. change of a feature's geometry, with respect to shape and location (moving objects)) and real-time sensor observations. This module enables the

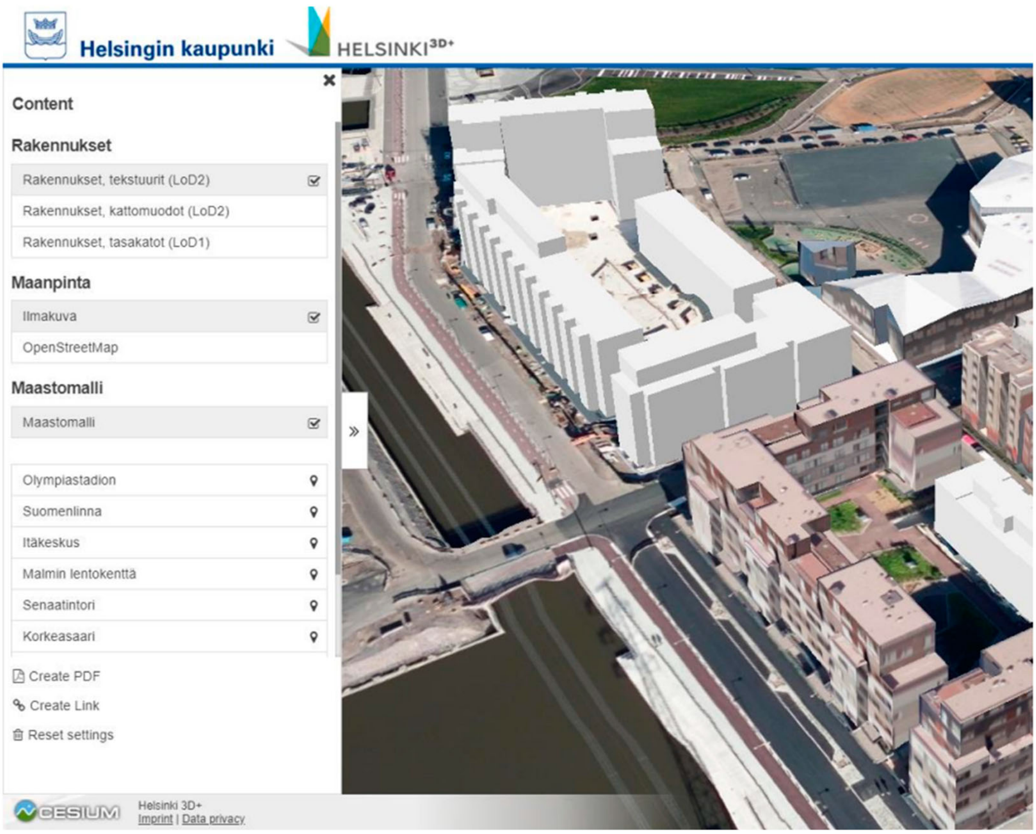

Figure 11. Combining reality mesh and CityGML to model buildings in Helsinki CDT (Helsinki 2019).

setting up of explicit links from city objects to sensors and sensor data services (Open Geospatial Consortium 2021).

While lacking data is a challenge in some places, in others there is sufficient data but there is insufficient data management (M. Zhu, personal communication, 10 August 2022). For example, efficiently updating both the City Information Model and the hazard data in the CDT is challenging (Schrotter and Hürzeler 2020) yet particularly important when it comes to time-sensitive and high-risk phenomena. According to (Shahat, Hyun, and Yeom 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 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, Yosri,

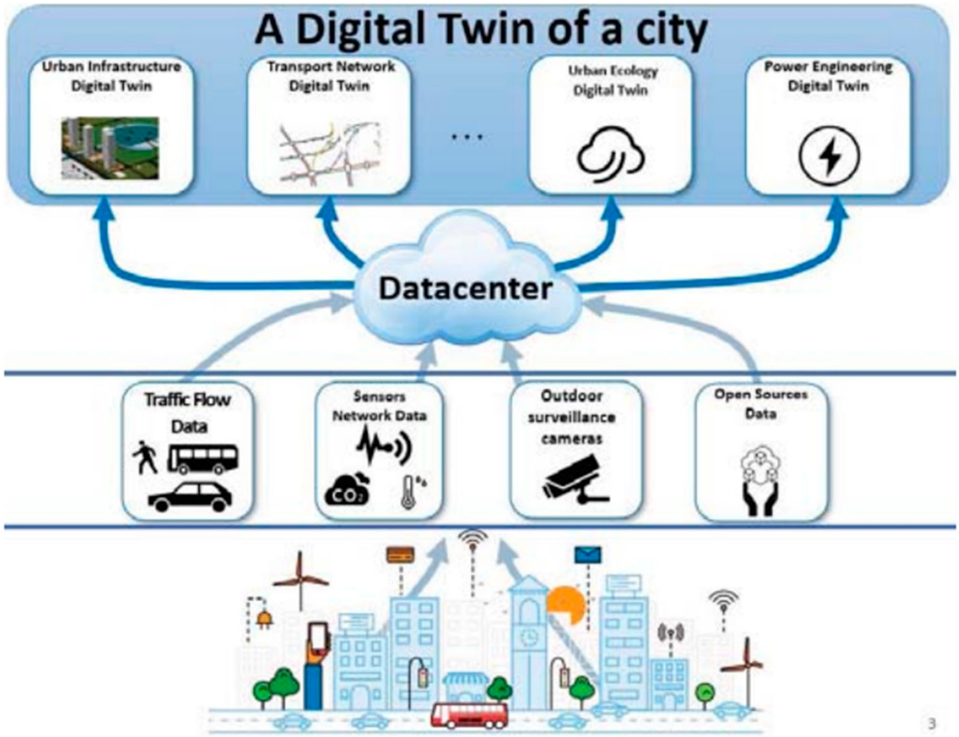

Figure 12. Conceptualizing a CDT data infrastructure (Ivanov et al. 2020).

and El-Dakhakhni 2021). The challenge is enabling the different models to interact with each other, in other words: facilitating their interoperability (Shahat, Hyun, and Yeom 2021).

To manage this translation, developers can implement 'interoperability translators,' software that regulates how systems interact with each other (Ghaith, Yosri, and El-Dakhakhni 2021). For example, in the case of the Calgary-based CDT designed to model floods, simulation outcomes will be sent to and from the simulation models and the translator software (e.g. GIS) until steady state results are obtained. Taking this interaction between models even further, Ford and 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', as shown in Figure 13. 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.

Another consideration in a multi-layered CDT is the high level of computing power required for running the many different models (Shahat, Hyun, and Yeom 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, Yosri, and El-Dakhakhni 2021).

Singapore is developing the 'Digital Urban Climate Twin (DUCT)' which builds upon its CDT to inform cooling strategies for the city (Aydt 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. 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

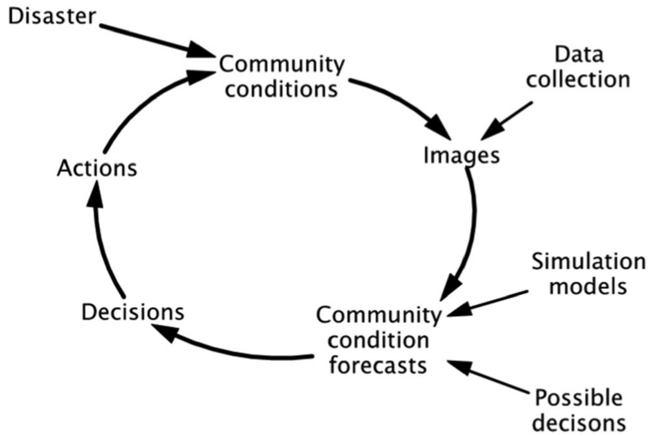

Figure 13. Model of iterative community disaster management (Ford and Wolf 2020).

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.

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 (M. Zhu, personal communication, 10 August 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 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, Hyun, and Yeom 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).

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, Loggins, and Wallace 2015) 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, Loggins, and Wallace 2015). '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, Loggins, and Wallace 2015).

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, Loggins, and

Wallace 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, participants proposed improvements on the accessibility and visual aesthetic (Dembski et al. 2020).

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 enables enhanced shape cognition and evaluation of complex spatial context as well as the results of analyses (Biljecki et al. 2015). 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 and Yang 2020). In the case of public interaction, a high level of detail might be needed to facilitate a 'spatial recognition of reality'. 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, Yamu, and Wössner 2019). It makes these renders visible via COVISE, which is an open source modular visualization system to support collaborative data visualization in virtual environments as well as on the desktop.

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, Hyun, and Yeom 2021). There may also be trade-offs 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 and 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. 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.

5. Conclusion

In a time of increasing urbanization, heightened risks from extreme weather, and developing smart technologies, this paper explored the potential for City Digital Twins (CDTs) to support urban areas in building their resilience to the various shocks and stresses they face. First, the various definition of urban resilience, smart cities and CDTs were explored, with an emphasis on the varying degrees of CDTinteractivity, data integration and interaction with the physical. In the results section, key characteristics that enable CDTs to contribute to resilience planning were described, 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. It was also noted that CDTs contribute to all six of the Community Resilience System (CRS) stages (engagement, assessment, visioning, planning, implementing, and monitoring and maintenance), leading to the conclusion that they have the potential to enhance urban resilience from a qualitative perspective (Nguyen and Akerkar 2020). Finally, 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 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.

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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
Anonymous (due to blind peer-review)
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 cover*	*Unknown*	*3D Buildings, vegetation, elevation (LiDAR)*	*Unknown*	*Cesium, TerraJS*	*Yes*
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,	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

(*Continued*)

Continued.

Project Name and Link	Location(s)	Resilience topic(s)	Phenomena modelled	Data	Interactivity	Software	Open source
		flooding, urban climate					
Multi-network interdependent critical infrastructure programme 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.