Smart Cities with Digital Twin Systems for Disaster Management

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Abstract: Exploiting smart cities with digital twins (SCDT) requires the integration of sensing and simulation across diverse infrastructure systems into community management. Community disaster management can provide a valuable foundation for SCDT development. The current work proposes and tests a conceptual model of a SCDT for disaster management and describes two threats to SCDT development that can be mitigated by focusing development on disaster management. Information loops, as opposed to individual components, are identified as a critical future focus of SCDT development. Primary contributions include support for SCDT development for disaster management, a conceptual SCDT for disaster management model, and a discussion of issues to be addressed in the development and deployment of SCDT for disaster management. **DOI: 10.1061/(ASCE)ME.1943-5479.0000779.**

Introduction

A community is a complex system of interacting systems that uses goods and services to benefit its residents. Some of those systems are built infrastructures, while others are social infrastructures. Examples of built infrastructures include roadways, storm drainage, electric power, and potable water. Examples of social infrastructures include governance, safety and security, health, commerce, and education. Built infrastructure systems (e.g., hospitals, offices, and retail centers) support people (e.g., residents, visitors, workforces), and social infrastructure systems utilize built facilities to serve populations. A community's evolution is driven and constrained by its infrastructures and the people that develop and use those infrastructures as they respond to internal and external forces and leadership decisions. The interdependencies and interactions among community systems create causal closed-loop management structures that impact community behaviors (Little et al. 2015; Oh et al. 2013; Rinaldi et al. 2001).

Disasters severely stress community system interdependencies by damaging or destroying built infrastructures, dislocating populations, and disrupting individual systems and their interactions. As a simple example, if a hurricane forces a large fraction of a community to evacuate, the diminished size of the construction workforce may constrain the rebuilding of homes, which would limit the number of people who can return to suitable housing. This constraint on repatriation could reduce future tax revenues available for recovery and the regrowth of the workforce and therefore commerce, which would further limit the rebuilding of residences. Therefore, effective disaster management interventions must influence both the community's systems and the interactions among systems and populations to achieve desired results.

Communities experience disasters in four phases: mitigation, preparation, response, and recovery (FEMA 2016; Thorvaldsdottir and Sigbjornsson 2013; St. Louis County 2018). Disaster phases evolve over different time horizons. Mitigation and preparation are ongoing operations, response evolves over days and weeks, and recovery evolves over months and years. Research supports this conceptualization. For example, Kates et al. (2006) found in the recovery of New Orleans after Hurricane Katrina that among the emergency, restoration, and reconstruction I and II phases each phase took much longer than the previous phase. Tamura (2007) found that the restoration of the lifelines, railroads, roads, and harbor facilities after the Great Hanshin-Awaji earthquake took 2 years, restoration of housing took 5 years, and economic recovery took over 10 years. The research also shows that disaster experiences and management are community- and disaster-specific and that communities evolve throughout a disaster experience. Therefore, significant progress in community disaster management requires capabilities that can synthesize the unique characteristics and conditions of a community during a specific disaster and anticipate the evolution of a community following a disaster. Smart cities with digital twins (SCDT) can provide these capabilities. The Smart Cities Council (2019) defines a smart city as one that "uses information and communications technology (ICT) to enhance its livability, workability and sustainability." Mikell and Mikell (2018) define digital twins as "the virtual representation of a physical object or system across its life-cycle." A SCDT brings these two components together.

When fully applied at a community level, SCDT present opportunities to greatly improve community management. For example, Singapore is actively pursuing becoming a so-called smart nation in an effort to improve human welfare, quality of life, and management of infrastructure (May 2019). Related to disasters, smart cities could use advanced technologies to sense the conditions of important systems, and digital twins could use virtual images for computer simulation of community systems to predict impacts of proposed strategies. A community-level SCDT integrates across built and social infrastructure systems, which are sensed and for which future conditions are forecasted with one or more digital twins. The real-time data available from smart city technologies can reduce the time to obtain data and improve decisions by providing

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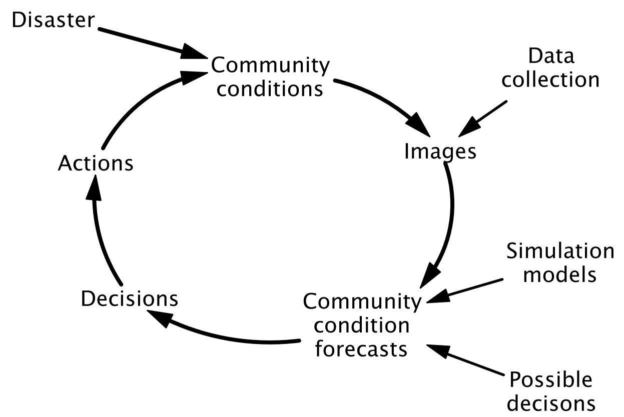

Fig. 1. A feedback model of iterative community disaster management.

additional information as disaster management leaders respond to conditions that often change quickly, requiring quick responses (Lindell et al. 2007). Digital twins can also improve and potentially optimize disaster management strategies by providing leaders reliable forecasts of the likely impacts of proposed decisions through fast and inexpensive experimentation. However, as will be described, SCDT has not yet evolved to capture these benefits, and additional work is required to develop SCDT at a community level for improved disaster management or general community management.

Fig. 1 (created in Vensim) shows a model of an iterative community disaster management cycle. In the response and recovery phases, data collection is applied to existing community conditions to develop images that are used in mental or formal simulation models to forecast conditions that will occur if different possible decisions are made. These result in decisions that lead to actions and changes in community conditions. Subsequent cycles adapt to changing community conditions as the disaster experience evolves. In the mitigation and preparation phases, a forecasted or approaching disaster and possible conditions are used in simulation and decision-making. SCDT can improve all four phases of a community disaster experience. In the mitigation phase SCDT can be used to evaluate alternative policies and plans to reduce loss of life and property and can thereby guide community leaders in disaster management investment decisions. In the preparation phase SCDT can be used to collect and analyze near-real-time data about community and disaster event conditions as the basis for proactive actions such as evacuations. In the response phase SCDT can be used to report damage and threats to lives and well-being and thereby improve first responder deployment. In the recovery phase SCDT can be used to identify rebuilding bottlenecks and effective and efficient means to build back better and to guide resource allocation strategies. A critical feature of the disaster management cycle depicted in Fig. 1 is that it does not conclude with a decision or even the actions that follow decisions—it is an iterative process that is repeated until a desired end state of community conditions is achieved.

The iterative nature of disaster management provides a particularly fertile environment for the development and application of SCDT. Disaster management can be investigated from multiple perspectives based on the number of communities, number of disasters, types of resources, or other characteristics. By looking at a single community through the lens of a single disaster, SCDT can be focused to provide improved tools to move through the disaster management cycle. The current work takes initial steps toward the use of SCDT for disaster management by describing reasons that SCDT should be developed for disaster management, proposing a conceptual model for how SCDT can be integrated into community disaster management information management, illustrating the model with examples from practice and discussing two threats to SCDT development that can be mitigated with a focus on disaster management.

Literature Review of Disaster Management Models with Applicability to SCDT

Disaster management models that describe a recommended process through a single disaster abound (e.g., FEMA 2011; UN-OCHA 2019). These high-level one-pass models focus on planning and do not "close the loop" through actions and changes in community conditions to address the iterative and adaptive nature of actual disaster management. For example, some information science models focus on data collection for developing images (e.g., Albuquerque et al. 2015; Ragini et al. 2018) or on simulation models to forecast community conditions (e.g., Choi et al. 2018). One specific example is Horita et al.'s (2016) oDMN model that links data and decision-making in disaster management. Other disaster models focus on economic improvement (e.g., Eid and El-Adaway 2017) or risk (e.g., Choi et al. 2019; Assaf 2011). These simulation models include models at a community level of aggregation that require interactions among infrastructure systems (e.g., storm drainage/flooding and transportation).

Some models of virtual systems include iteration with the real (physical) world (e.g., Hastak and Koo 2016), typically without using SCDT terminology. Models of disaster management that are relevant to the current work include those that address an evolving disaster experience and address multiple infrastructure systems. This requires an iterative model of repeated and adaptive decision-making that reflect the role of information in those decisions, such as a more specific version of a portion of Grieves's (2008) digital twin production process. Only a few disaster management models reflect this iterative process. For example, the Asian Disaster Preparedness Centre (ADPC) said, "It is important to consider recovery as a continuum rather than as a distinct phase of the disaster management cycle" (ADPC 2015), and it uses its Asian Disaster Preparedness Model (ADPC 2015).

However, the ADPC model is iterative across multiple disasters, whereas the current work focuses on the management of a single disaster. A second iterative model by Ford and Keith (2016) developed a relatively simple simulation model of the disaster recovery phase that focused on the role of different types of social capital on recovery from a disaster. Fig. 2 provides a conceptual model of the primary causal feedback structures in the Ford and Keith model using a causal loop diagram. See Sterman (2000) for a description of causal loop diagram modeling. In the Ford and Keith model, a shock event interrupts a community's underlying growth or decay trend (Feedback Loop R1), which is limited by both physical constraints (Feedback Loop B1) and crowding (Feedback Loop B2). Strong social infrastructures can reverse community decay or accelerate recovery through investment or volunteering (Feedback Loop R2).

Most previous smart city, digital twin, or SCDT development work that could be used for disaster management addresses a single infrastructure system, an infrastructure subsystem, or an individual asset. The most common infrastructure system examples include transportation systems (e.g., Gibson et al. 2007; Lee et al. 2016; Rosencrance 2018; Yan et al. 2018; May 2019) and stormwater and water quality systems (e.g., Heaton 2012; Klenzendorf et al. 2015; Howell et al. 2017; Chen and Han 2018; Mullapudi et al. 2018). Other investigations address other types of systems, including

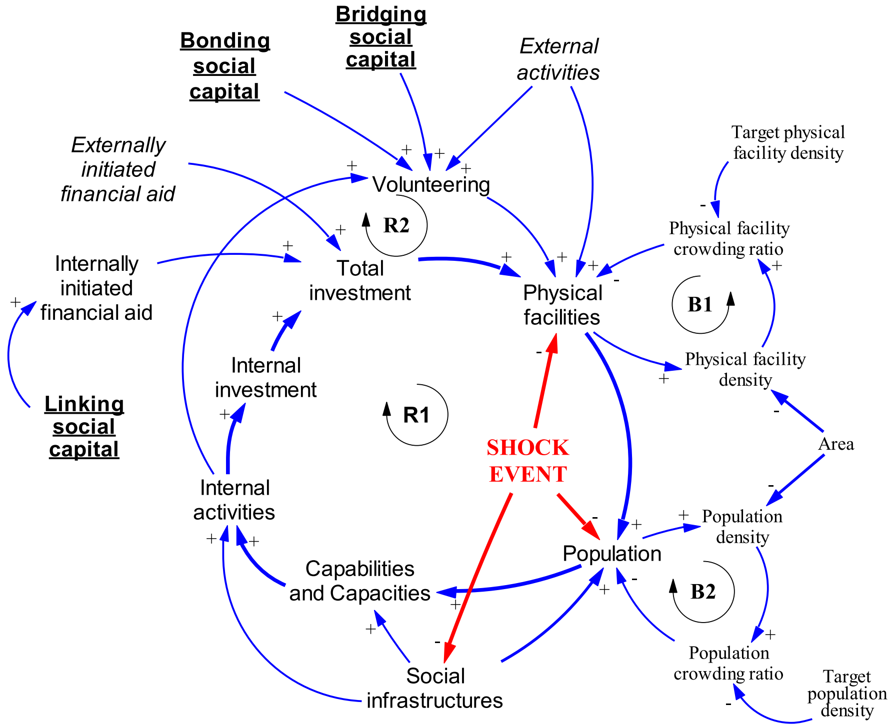

Fig. 2. Disaster recovery phase simulation model. (Reprinted from Ford and Keith 2016.)

cyber-physical systems (e.g., Alam and Saddik 2017). Examples of SCDT that cross infrastructure system boundaries are rare. Current efforts toward integration across infrastructures, such as in Shanghai (Li et al. 2018) and Atlanta, show potential. For example, in Atlanta, a virtual reality–based digital twin has been developed that allows for the investigation of human interactions with infrastructure (Mohammadi and Taylor 2017).

In summary, most disaster management models fail to address one or both of the following: iterative disaster management processes or community infrastructure interactions. SCDT can help address both gaps. A fully developed SCDT could provide integrated community-level data, images, and simulation, thereby closing the disaster management loop virtually, and thereby improving forecasting of the outcomes of anticipated actions and providing feedback on the impacts of actions taken.

Improved Definitions

Smart city and digital twin definitions are evolving, with both terms being used for various purposes. Some smart cities are defined based on planning to be sustainable (Yigitcanlar et al. 2018) or to improve the quality of life without burdening future generations (Zhao 2011). Other smart cities are defined by how they plan to be highly connected digitally and use those data to improve transparency and governance (Caragliu et al. 2011), how they use advanced sensors to collect and distribute critical data in real time to optimize resources and services to citizens (Hall et al. 2000), or how they use data to improve the overall quality of life (Piro et al. 2014). Consistently in the literature, smart city definitions depend upon the target community's underlying goals, and this leads to a diversity of definitions.

Likewise, digital twin definitions are evolving. Work on product information by Grieves and NASA in the early 2000s evolved into what are now known as digital twins. He suggested four types: prototypes, instances, aggregations of twins of subsystems, and twins that integrate with their environments (Grieves and Vickers 2017). Current definitions appear to be driven by the underlying objectives of the digital twin developer. For example, some digital twin definitions include a "link between a real world object and its digital representation that is continuously using data from the sensors" (Intellectsoft US 2018), a "method of visualizing the feasibility and better methods in a prompt and affordable manner by reproducing systems and activities in the physical and digital worlds in real-time (like twins) by simulating control and management" (NEC 2019), and "the virtual representation of a physical object or system across its life-cycle" using "real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making" (Mikell and Mikell 2018). Digital twin development also varies across scale—from equipment to buildings to cities. At the city scale, digital twins are used to support the assessment of individual infrastructure system performance, such as transportation or flood systems, when faced with an assumed set of input conditions (Li et al. 2018). In these applications, the digital twins do not necessarily require the use of sensors to perform their function.

The variability in smart city and digital twin definitions poses a challenge when applying them to cities. By their nature, cities are difficult to model because they are combinations of dynamically interacting infrastructures and populations that are subject to highly variable external influences, including atmospheric, hydrologic, socioeconomic, or other factors. Definitions such as the aforementioned ones cannot adequately contribute to SCDT for community management or community disaster management purposes. Improved definitions for community disaster management are proposed next.

Smart City

The *city* part of a smart city implies a communal benefit, versus benefits captured only by individuals or small portions of a

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community, such as a single building, neighborhood, or even a single infrastructure system. The *smart* part of a smart city implies that information and communication technologies (ICT) are used to improve not only data collection efficiency but also decision-making. For example, smart metering technology for electric power and water systems does not necessarily make a city smarter unless the data are used to create a benefit, such as management of a brownout or water shortage. Likewise, so-called big data efforts are not necessarily smart city efforts unless the data are collected and analyzed in real time to improve decision-making.

To improve decision-making under adverse conditions, such as a disaster, smart city systems require at least two features. First, the system must use ICT sensors to provide real-time data in a way that leaders or the public can interpret to make decisions. Second, the system must be able to provide sensor data autonomously. The autonomous requirement distinguishes smart city systems from historical man-in-the-loop systems that depend on humans to manually collect data. Autonomy is particularly important in the application of the smart city concept to disaster management because humans are often unable to carry out functions during and after disasters owing to an inability to get to required measurement locations or information centers.

To better meet these definitional needs, as used here, smart cities are *communities that use ICT to autonomously sense, store, and make current information on community conditions that is easily available to community leaders and citizens*.

Digital Twin

Two characteristics of a digital twin are needed to improve community disaster management decisions. First, the digital twin must include one or more community images. These images can include community features, their characteristics, and the interactions among community components. The images can take any of several forms, including visual maps, lists of assets and their conditions or state of damage, or other forms of descriptions of conditions. Interactions among community components can be captured in qualitative models such as interaction diagrams or in the structures of quantitative models such as formal simulation models. These images are different than the raw data that are stored in the smart city portion of SCDT in that information value has been added by arranging and presenting the data into images for use in community disaster management. Second, the digital twin may include one or more computer simulation models with the ability to bring multiple, nascent images and data together to predict possible future conditions. While human mental models have historically been used to simulate future conditions and should continue to play an important role in SCDT, the complexities of community disaster management require computer simulations to accurately forecast features, characteristics, and interactions. For example, a digital twin of a large stormwater basin could use information from a flood map in a model of the interactions between flooding and roadways to predict the location and capacity of available egress routes much more accurately than any human. Optimally, a community's digital twin would predict conditions across all critical infrastructure systems.

The images and outputs from simulations in a digital twin must also inform decision-making. One measure of success should be the value of decision support provided by the image or simulation output. Therefore, interinfrastructure digital twins can provide much more value than single-system digital twins alone. For example, a flooding/transportation digital twin that provides both available egress routes and alternatives to flooded roadways is more valuable than a flood map and flooding predictions alone or a roadway map and traffic congestion forecasts alone.

To better meet these definitional needs, as used here, digital twins are *community images and simulations of infrastructures that can be used to present current and forecast future conditions in ways that improve decision-making and future conditions*.

Smart City Digital Twins

A SCDT brings together smart city and digital twin technologies into a single platform. However, a distinction between smart city and digital twin functions is important for evaluating SCDT use and improving SCDT development. This is particularly important for the application of SCDT for community disaster management because the data collected by smart city tools can be used both immediately by decision makers and the public and as an input to digital twins that provide future condition insights. The current work distinguishes between the smart city and digital twin parts of SCDT in two ways. First, smart cities collect and disseminate data, often in real time, but do not forecast future conditions. Second, digital twins do not collect condition data, but rather use collected data to create information and forecast potential futures. To support community disaster management, a SCDT must use current data (smart city) to drive a simulation (digital twin) that allows decision makers to assess and evaluate potential future conditions based on current conditions and possible impacts of decisions.

To better meet these definitional needs, as used here, a SCDT is *a system of ICT sensors that develop data sets integrated into digital twin models that provide a dynamic ability to assess the future impacts of current conditions and strategies in ways that improve decision-making to achieve desired future results*.

Two Reasons to Develop SCDT for Disaster Management

Developing SCDT that meet the previously given definitions poses challenges, notably understanding how to model complex interactions across city systems. Disaster management provides opportunities to address these challenges in two ways. First, SCDT meet the needs of disaster management particularly well. Second, disaster management provides a microcosm for SCDT development, integration, and application.

SCDT Meets Disaster Management Needs Particularly Well

Developing SCDT for disaster management captures outsized benefits through the synergy of unmet disaster management needs and SCDT capabilities. Effective disaster management requires condition data on multiple, diverse, connected infrastructures simultaneously. For example, evacuation decisions based on coordinated evacuation route traffic volumes and flooded highways data are better than decisions based on transportation or storm drainage system data alone. Further, selecting efficient resource allocations in each of the four disaster management phases among several alternatives requires diverse data sets that human capital is often unable to collect and disseminate due to the event. *How can managers acquire all the data needed to choose effective and efficient strategies during a disaster?* Some existing smart city technologies are particularly well suited for disaster data collection and transmission because they can operate without humans to provide information to managers, provided they are supplied with the capabilities to continue performing in disaster conditions. Flood gauges with automated reporting are an example. The development of smart city technologies for disaster management will improve data collection capabilities and fully exploit the advantages of smart cities over traditional data collection.

Community conditions often change rapidly during disaster response and recovery phases. Therefore, disaster managers need current data on community conditions in order to make the best decisions. *How can disaster managers acquire current community conditions when those conditions change quickly?* Smart city technologies are uniquely able to meet this need by providing near-real-time data, often more reliably than human-based forms of data collection and reporting. This means SCDT can be used to significantly improve disaster management.

In addition to current condition data, making the best disaster management decisions requires knowing and understanding the unique characteristics of a specific community. The complex interactions of community systems make accurate forecasts of the primary and secondary impacts of disaster management decisions impossible for humans alone. *How can disaster managers accurately forecast the interdependent impacts of their decisions?* Causal simulation models integrated as digital twins with smart city technologies can capture these interactions and explain how management choices influence multiple community systems and disaster management performance metrics. By providing disaster managers with accurate forecasts of the impacts of their choices and an improved understanding of those forecasts, SCDT can improve disaster outcomes.

Some disaster management strategies are likely to dominate in many common disaster/community circumstances. For example, experience shows that restoring electrical power can speed recovery because many other community functions depend on that power. Other lessons about effective strategies may be disaster or community specific. For example, after a hurricane, the availability of residences may constrain the size of the construction workforce and therefore recovery (including the rebuilding of residences), making this a critical management focus. But this may not be true after an earthquake, where disruptions to transportation networks could have the highest impact. *How can disaster managers learn, especially during disaster mitigation and preparation, about the strategies that will perform best during disaster response and recovery?* Digital twins of communities provide opportunities to learn through fast, inexpensive virtual simulation–based strategy testing and experimentation. Many valuable disaster management lessons are likely available through the development and exercise of generic community digital twins, such as sequences and capacity levels of community infrastructures that, if restored, improve recovery speed and quality. Community- and disaster-specific strategies can also be developed and tested with digital twins that reflect specific circumstances. Therefore, the development of SCDT for disaster management can accelerate learning about disaster management strategies and thereby improve disaster experiences for communities. These benefits make community disaster management particularly attractive as a setting for SCDT development.

Disaster Management Provides a Microcosm for SCDT Development, Integration, and Application

Developing a SCDT for an entire community and its associated management decisions is a significant jump for the technologies and approaches that exist today. Work to date typically addresses individual infrastructure systems to improve communication of conditions. But there are exceptions, such as the Flood Early Warning System in Austin, Texas. This system uses continuous data collection and models of natural drainage patterns to generate precise flood maps and future impacts to roadways, thus providing linkage of two infrastructure systems (City of Austin 2018). This SCDT is effective even though it only links two infrastructure systems.

Compared to more general community management, however, disaster management provides a microcosm that more narrowly defines the objectives and the data required to make decisions and, therefore, the SCDT development requirements. Further, many disaster management decisions mirror normal operating community management decisions, albeit with heightened importance on getting the correct answer quickly. Once developed for disasters, these systems can be expanded to incorporate elements necessary for community planning and management on a continuous basis.

Disaster management also benefits general SCDT development by connecting the critical physical and social infrastructure systems of the community to the *minimum* information required to manage a city through a crisis. As such, disaster management supports SCDT development by accelerating the foundational work of a broader community management SCDT without the need to solve all community management challenges while building the initial system.

Since disaster managers are more concerned with community operations than fidelity of model representations to actual appearance, a disaster management SCDT can focus on functionality instead of visual presentation. This can speed the development of an effective SCDT and ease long-term maintenance. In a disaster, the best use of a digital twin would be to exploit its power to explain the interactions of physical and social infrastructures with strategies within the community and their impacts on the community. Therefore, digital twin developers do not need to create a perfect mirror image of a city, only a functional image it—something that can be accomplished with existing systems modeling approaches and much less data.

Finally, disaster management provides a functional testbed with relatively deep data sets that can be used to test and develop confidence in the ability of a SCDT to support a community through a disaster experience. While no two disasters are identical, the data streams leaders need, and decisions leaders must make, are relatively consistent. For example, hurricanes, tornadoes, and earthquakes all destroy or damage residences, forcing community leaders to make decisions about temporary housing and the allocation of scarce resources for rebuilding. Since data sets from previous disasters are relatively available, disaster management provides a platform to test SCDT and generate relatively quick insights into the performance and benefits of proposed SCDT solutions.

Disaster Management with SCDT

To facilitate the development of a model of a SCDT that supports disaster management, a sample of publicly available literature in research journals, mass market publications, SCDT project reports, and community and corporate webpages were searched for information on smart city and digital twin projects; 378 publications were reviewed. Of these, 198 described applications to a specific community or community system (versus a technology or single asset, for example). Adequate information was collected to assess 47 smart city, digital twin, or SCDT systems describing the community, infrastructure system, scale of application, level of development, smart city description, digital twin description, and application to disaster management. Within these systems, 66% (31) modeled transportation systems, 38% (18) modeled water utility systems, 28% (13) modeled buildings or facility management systems, 11% (5) modeled electric utilities, 6% (3) modeled waste systems, and 6% (3) modeled environment systems. Totals do not equal 100% (47) because some of the systems included multiple

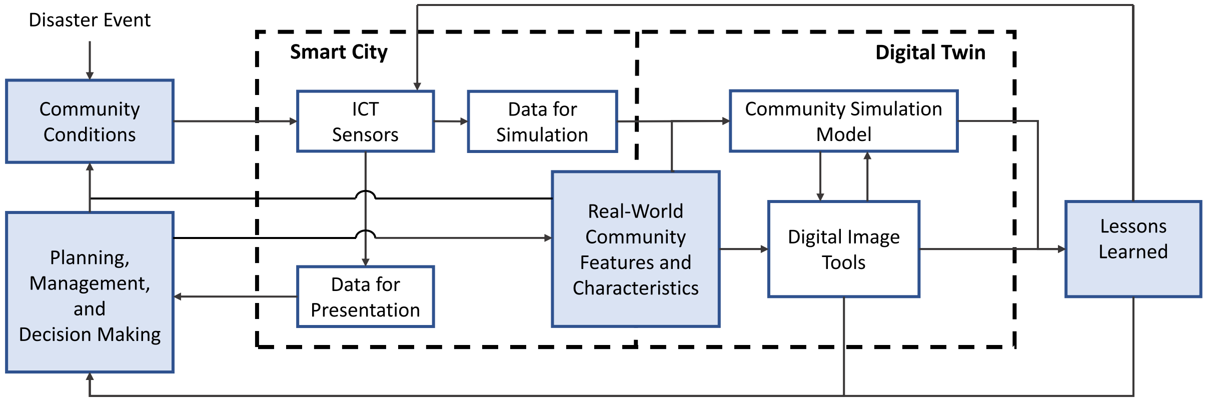

Fig. 3. Community disaster management model with a smart city digital twin.

types of infrastructure systems. Descriptions of the systems reviewed are available from the authors.

The review identified components of a SCDT that could be used to support the iterative disaster management model described in Fig. 1. The model in Fig. 3 (created with Microsoft PowerPoint) shows the minimum combination of components and information flows for a SCDT to effectively support community disaster management. Like the iterative model in Fig. 1, this model describes disaster management with continuous SCDT monitoring of community conditions to reflect the impacts of decisions as they are made and actions as they are implemented. However, the model also shows how lessons learned from the SCDT can be used to improve decision-making and the sensor capabilities of the SCDT itself.

The model has three principal parts: (1) components that are not a part of the SCDT itself but are impacted either directly by the SCDT or through lessons learned from the SCDT, (2) smart city components, and (3) digital twin components. The three parts of the model are described next.

Some of the model components (shaded in Fig. 3) exist outside a smart city or digital twin. These components connect the SCDT to the community and the disaster event and include Community Conditions, Community Features and Characteristics, and Lessons Learned from Community Simulation Model and Digital Image Tools. These components also include information on community decision-making and the resulting impacts of those decisions on the community's ability to respond to the event. Community Features and Characteristics overlay the SCDT and define the community infrastructure systems (e.g., the maximum capacity of the freeway system). Management decisions directly impact community features and characteristics with respect to timing and capacity/capability. For instance, a management decision to focus on the recovery of housing infrastructure (e.g., by clearing debris) will increase the housing capacity by increasing the space available for housing and thereby have an impact on the ability of the workforce (a community feature) to return to the impacted area. In contrast, Community Conditions define the performance or utilization of those infrastructure systems. Building on the housing example, the percentage of housing available for workforce housing would be a community condition. Community conditions can be impacted by an external event, such as a disaster, management decisions, decisions by the public, or by changes to community features and characteristics that alter the limiting capacities of an infrastructure system. In some disaster events, such as major tornadoes or earthquakes, community features and characteristics are fundamentally altered. However, this model is built to assist community leaders with the use of SCDT for disaster management. As such, a community feature or characteristic is not changed until a management decision is made to leave that element in its damaged state. Thus, the disaster event is assumed to only impact the condition of the community, while management decisions can impact community features and community conditions. Finally, the SCDT generates insights that drive fundamental changes in perspectives about the community during and after a disaster event. These lessons learned impact planning and management decisions and sensor choices.

The smart city component (Fig. 3, Smart City box) includes the sensors that generate data necessary to drive the SCDT. These data can be used for two purposes: (1) as input for simulation and adjustments to the digital twin, and (2) as data presented to community residents and leaders for decision-making. The data for presentation does not necessarily have to be graphic to be effective in the smart city component. Road closure information provided to drivers on electronic billboards, for example, is a form of data presentation that is not graphic that could be part of a disaster management SCDT. Color-coded current traffic speeds is a form of data for presentation that is graphic. Both can provide the community with immediately beneficial information in a disaster event.

The digital twin component (Fig. 3 Digital Twin box) includes a suite of tools that use data from the smart city to generate digital images of a community, as well as simulation modeling to provide decision makers with predictive information about future conditions. Digital image tools include models of the various physical and nonphysical infrastructure systems that define the community and its interactions. In addition, those images can, and optimally should, also reflect the spatial constraints associated with the community. Some digital twins of specific hazards and disaster management issues address these needs (e.g., Kim et al. 2006). Digital twins for communities need to do the same on a larger scale. The Community Simulation Model uses information from the digital image tools and the real-world community's infrastructure systems features and characteristics to predict future conditions. Future conditions could be impacted by current system conditions or by decisions that alter the community features and characteristics.

Finally, the arrows in the model indicate flows of information or actions that impact community conditions. Together, the SCDT components and information flows describe several loops that show how information within a SCDT could be iteratively used throughout a disaster to make decisions and to assess the efficacy of those decisions. For example, sensors could provide traffic speed data for presentation that are immediately distributed to the public and other decision makers, whose decisions about evacuation will impact road closures, congestion, and traffic speeds, which will be reflected in updated speed data.

The information loops that drive the model exist without a SCDT and have been used manually during disaster management. The development of these loops within a SCDT improves the speed of these processes by removing the time necessary for humans to collect and process data. For example, as information is generated by the smart city, it impacts forecasting by the digital twin, which can be used to make management decisions and take actions that the smart city can monitor and feed back in real-time to the digital twin for further forecasting. As community conditions recover and community features and characteristics are adjusted, the smart city and the digital twin can provide information on the effects of those changes and potential future conditions, respectively, with speeds that humans cannot achieve.

Discussion

The development and application of SCDT for community disaster management has the potential to save lives, reduce property damage, and accelerate economic restoration. However, these systems are still mostly in their infancy. For example, the need to model the multitude of dependencies among the diverse community infrastructures required to fully manage a community disaster has been clearly identified (Mohammadi and Taylor 2017), but no SCDT systems are known that do so. SCDT systems face many challenges with respect to community-level development as well, including limited sensing technologies, digital twins that do not accurately reflect community processes and characteristics, communication systems incapable of transferring the data necessary to capture a community's conditions, data insecurity, privacy issues, and others. While technological advances present opportunities to overcome these challenges, there are at least two important but inadequately addressed risks to SCDT development and deployment to manage a community through a disaster. First, infrastructure system or individual technology-focused SCDT development will miss critical community-level interdependencies across systems that drive community management decisions, especially during a disaster. Hereafter, this is referred to as integration risk. Second, the development of SCDT systems may stop or be constrained if SCDT applications do not provide meaningful benefits before funding and attention moves to other potential solutions. Hereafter, this is referred to as fatigue risk.

Mitigating Integration Risk in SCDT Development

On its current path, SCDT development will be constrained by a lack of work to integrate components into complete management cycles, creating an integration risk that will limit the benefits that these systems can provide community decision makers. Disaster management researchers have identified modeling system interdependencies as being critical to exploiting technology for disaster management (Little et al. 2015). But SCDT development to date appears to focus on individual SCDT system components, technologies, or individual information links. To better understand this, the previously noted 47 example systems were reviewed for a focus on individual system parts versus information loops using the disaster management model presented in Fig. 3.

Each of the individual information flows in Fig. 3 is represented in at least one of the 47 example SCDT systems. There are also high frequencies of component development in some of the systems. However, none of the examples reviewed describe a complete iterative loop or multiple iterative loops. Three connections are underrepresented: (1) the impact of decision-making on community conditions, (2) the impact of real-world community characteristics on changes in community conditions, and (3) the interaction of simulation models vital to forecasting community conditions with the digital imaging tools of the digital twin. The absence of these connections prevents complete iterative loops. The development of these linkages will be required to achieve the disaster management cycle presented in Fig. 1.

Technology-focused research and development may favor a focus on individual components or links, but community managers most value improved decision-making and insight. Addressing this need requires technologies that are integrated into a tool that facilitates an iterative cycle of decisions, actions, and follow-up leading to more decisions. Integration of this nature has been successfully developed between pairs of systems, such as in the Flood Alert System 4 in Houston (see Appendix). To improve data collection and digital representation of real systems, SCDT development should focus on integrating disaster management processing loops that drive iterative cycles as opposed to only the development of individual technologies.

Mitigating Fatigue Risk in SCDT Development

In aggregate, the challenges faced by SCDT developers mentioned previously create a particularly difficult risk to SCDT success—fatigue risk. As used here, fatigue risk in SCDT development is the possibility that development supporters will grow tired of waiting to capture benefits that justify their support and therefore withdraw or curtail support, preventing complete SCDT development. Financial sponsors are perhaps the most important supporters, but the public officials that facilitate development, public organizations and employees that will operate SCDT systems, and the public that are promised large benefits are also critical supporters. Fatigue risk is a threat to the development of SCDT for community management in general, as described earlier, as well as for the development of SCDT for disaster management.

Successfully managing fatigue risk is a part of crossing the "valley of death" from initial technology research and development to providing tangible value. The valley of death is a metaphor for the difficulty experienced by innovators in transitioning technologies that have been successfully researched and initially developed into successful applications. The valley most often includes a lack of funding and other forms of development support to progress from late research through technology development to application (Pusateri et al. 2015). The metaphor has been applied to the experiences of a wide range of products, including both incremental improvements and disruptive innovations, in many industrial and public settings. When applied to SCDT for community management, fatigue risk is particularly difficult due to the diversity of stakeholders and objectives, the discrete and competing technologies, and integration challenges.

Disaster management can help SCDT developers mitigate fatigue risk and successfully cross the valley of death. Disaster management offers an opportunity to establish adequate complexity to develop a useful community-level SCDT and limit fatigue risk in SCDT development. Successfully developing community-level SCDT requires technologies, tools, and methods that produce meaningful results that stakeholders can capture before fatigue depletes their faith in SCDT and their support. Developing SCDT requires significant time. For example, the smart Texas Border Crossing project took 10 years to plan and develop before it was put into operation in 2013 (Texas A&M Transportation Institute 2019). Developing SCDT to improve the disaster management cycle can provide the relatively quick, very meaningful, and valuable results needed to keep SCDT development advancing. Possible outcomes from disaster management SCDT development and use include improved feedback structures related to decisions made during an event, accurate explanations of why some recovery strategies work better than others, objective and data-supported disaster management guidelines, and improved strategies for community resilience.

Other SCDT development risks impact the management of integration and fatigue risks. One relates to SCDT ownership. SCDT ownership by any organization with limited or biased perspectives of the community will increase integration risk. SCDT ownership by any organization with a short time horizon, such as might be created by the need for accelerated financial gain, will increase fatigue risk. Therefore, to increase SCDT success opportunities, SCDT development and operation should be controlled and managed by public entities that have access to commercial, institutional, and private expertise and are informed by the participation of diverse community stakeholders.

Conclusions

Smart cities with digital twins have the potential to make significant improvements in community disaster management. Improved definitions of the terms smart city, digital twin, and smart city with digital twins clarify their roles in improving communities and distinguish between the two parts of a SCDT system. Two arguments support the development of SCDT for disaster management: (1) the intersection of SCDT capabilities and disaster management cycle needs, and (2) the focus disaster management gives to facilitate SCDT development. A SCDT system model is proposed that identifies system components and information flows. In addition, a disaster management focus in SCDT provides an approach to mitigating integration and fatigue risk in SCDT development.

The current work supports disaster management as a community management subset that can accelerate SCDT development by providing focus and valuable information. SCDT development is potentially threatened by the need to cross the valley of death from advanced research to application during which SCDT benefits may not appear fast enough to sustain development support. SCDT for disaster management can help cross the valley by accelerating the capture of benefits for community leaders and other stakeholders. SCDT development can benefit from expanding the focus from one or a few adjacent components to information processing loops that reflect how SCDT systems can impact the management of communities. The cumulative result is a strong argument for the development of SCDT systems focused on community disaster management.

The current work contributes to SCDT development in several ways. First, improved definitions are developed that more specifically describe the requirements of each SCDT part. These definitions can improve the quality of descriptions and discussions about SCDT development. Second, two synergies of SCDT and disaster management are described. These can be used to support SCDT development in this domain. Third, a new model of information flows and components in a disaster management SCDT system has been provided that can be used to model, describe, and evaluate SCDT projects and their potential impacts. Fourth, two important risks to SCDT development and deployment success (integration and fatigue) are identified and described, with descriptions of how a focus on disaster management can help mitigate those risks. These results can guide SCDT developers and increase the likelihood of SCDT development project success and, thus, SCDT success.

The results and conclusions of the current work are limited by the assumptions used and constraints on the work, which suggest future research opportunities. The current work focuses on disaster management. Other community-wide applications of SCDT may also offer advantages and ways to mitigate development risk. Appropriate for civil engineering, the current work focuses primarily on physical infrastructures. Additional work can also address the roles of social infrastructures in disaster management and their interactions with physical infrastructures. The level of aggregation for the current work included community systems and subsystems, whereas most current SCDT work is at smaller scales, such as individual buildings or parts of infrastructure subsystems. Additional work may reveal other significant areas of SCDT development or components in a SCDT system that can be added to the model presented here. Additional risks to successful SCDT development can also be identified and explored. The current work also addresses digital twins based on the potential for simulation to forecast future conditions, but it does not address the quality of forecasts or the impacts of forecasted conditions on adjacent infrastructure systems.

Future work can develop the system models necessary to use smart city data in multi-infrastructure system simulations. Particular issues relate to the data and models required to forecast with SCDTs. The ability to model critical system interactions is essential. Several existing approaches, such as system dynamics, design structure matrices, and agent-based modeling, can be effectively applied to these efforts. Adequate data for modeling and forecasting is, and will remain, a primary challenge, which can be partially addressed with new sensor technologies.

In closing, smart city digital twins can benefit from development that focuses on disaster management, and disaster management can be greatly improved by the development, adoption, and use of smart cities with digital twins.

Appendix. Flood Alert System 4, Houston: Example

Starting in the late 1990s with Flood Alert System (FAS) 1 and continuing to the present with FAS 4, a system with the characteristics of the model shown in Fig. 4 has been informing decision makers on rainfall events in Houston's Texas Medical Center (TMC). This system integrates rainfall data, collected approximately every 5 min, with hydrologic modeling capabilities to predict the peak flow and height of a runoff hydrograph in Brays Bayou and the associated backwater effect in the Harris Gully catchment, which discharges to Brays Bayou (Bedient et al. 2013). The system has shown itself to be accurate across a variety of events. For example, during a May 2015 flood event, it predicted the peak flow in Brays Bayou within 0.83% of the observed peak flow. Moreover, it predicted the time of the peak flow within 35 min of the actual peak over a storm event that lasted nearly 12 h (Bedient and Bass 2019). Further, the FAS is integrated into the TMC flood protection systems, providing the TMC with 2–3 h of advance notice to activate its flood defenses (Bedient and Bass 2019).

Fig. 4 (created with Microsoft PowerPoint) maps the FAS to the model presented in Fig. 3. Bold lines highlight information flows expressly identified in the literature referenced earlier. Solid, nonbolded lines indicate information flows implied from the literature. Dotted lines indicate information flows not expressly identified or implied in the literature. Reviewing Fig. 4, certain items are notable. First, lessons learned are used to improve the number and location of the sensors that provide data for the system. Second, smart city data can be presented directly for decision-making or packaged to feed simulation models. Finally, the digital twin creates outputs through digital imaging tools that can be directly used by decision makers to protect critical infrastructure such as the TMC.

The FAS supports completion of the disaster management loop from a decision to a change in real-world features—specifically,

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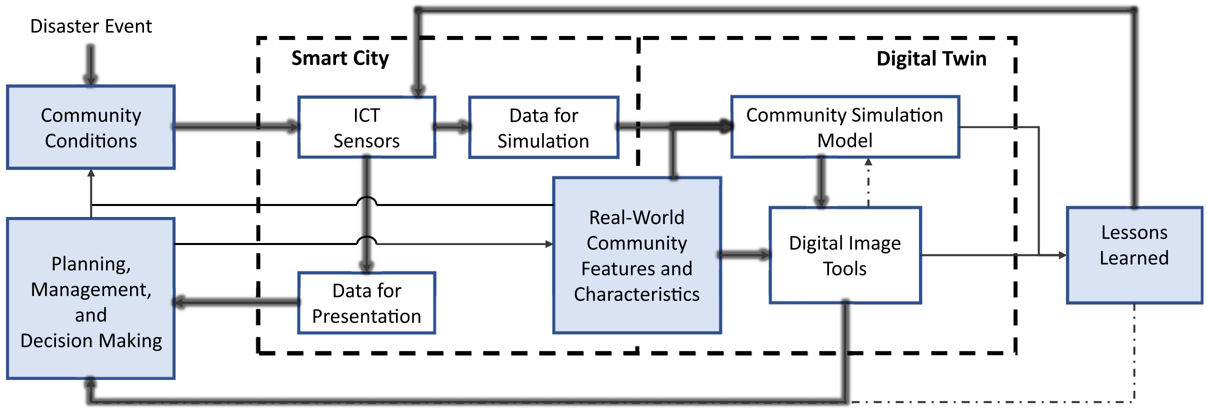

Fig. 4. Map of FAS smart city digital twin.

engaging flood defenses at the TMC—that affects community conditions by reducing or eliminating flood impacts. It also provides the opportunity to monitor and predict when the flood defenses can be removed. While the focus of the FAS is to prevent a disaster, it constitutes valid proof of how a SCDT can be utilized to improve disaster management across each of the four phases.

Data Availability Statement

Some or all data generated or used during the study are available from the corresponding author by request, including diagrams of the original figures and information on the 47 examples.

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Supplemental Data

The data on the 47 examples are available online in the ASCE Library (www.ascelibrary.org).

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