Smarter Cities: Exploring the Applications of Emergency Management through Digital Twin Technology

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Abstract: Today, the world is urbanizing at an extreme rate. According to The World Bank, "56% of the world's population – 4.4 billion inhabitants – live in cities". This trend is expected to continue, with the urban population more than doubling its current size by 2050, at which nearly 7 of 10 people will live in cities (WB, Overview, n.d.). This large concentration of people contributes significantly to the destruction of natural environments and increases global warming, causing climate change. The UN Environment Program stated that "cities are responsible for 75% of global CO2 emissions" (UN-EP, 2017). This allows a culminate and amplify their disastrous effects that put 44% of world population at risk of being submerged due to rising sea levels or be subjected to flooding. When a high-risk disaster situation occurs, such as flash flooding, hurricane, or building fire, every second counts. Several gaps exist in the functionality and efficiency of current emergency management within many U.S. cities. Such issues include but are not limited to deficiencies in inter-organizational communication, inefficient deployment of resources, and potential weaknesses in public notification methods. One possible solution to bridge those gaps is through the application of Digital Twin technology. This paper discusses the potential integrations of a Digital Twin City with existing emergency management systems to mitigate large-scale, complex disaster situations within the built environments.

INTRODUCTION

The world is becoming more urbanized, with 56% of the world's population living in urban area (Ritchie & Roser, 2018). It is expected that 68% of the world's population will be residing in cities by the year 2050 (Magle et al., 2019). Cities consume 75% of natural resources and are responsible for 75% of global CO2 emissions. Climate change and global warming causes sea levels to rise with an expectation of extreme upsurge (Figure 1), that increases the number of extreme weather events such as floods, droughts, and storms (UN-EP 2023).

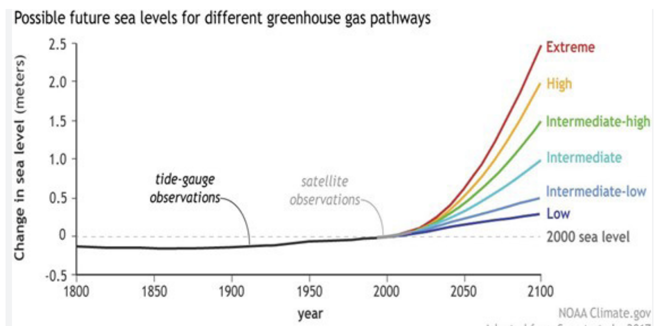

Figure 1. The prediction of sea level rise between 1800-2100 (NOAA, 2017)

Within the past 50 years, there has been a significant increase in the number of natural disasters and the global economic losses associated with them. The United States alone has accounted for more than one-third of these losses due to various weather-, climate-, and water-related causes, "killing 115 people and causing US$ 202 million in losses daily." (WMO, 2021). Figure (2) illustrate the U.S. 2023 losses due to weather and climate change related disasters (NOAA, 2023), and Figure (3) shows the significant increase in these losses in the recent years.

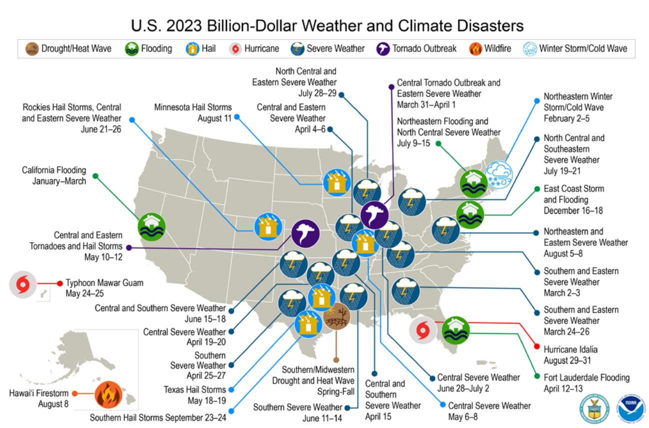

Figure 2. "U.S. 2023 Billion-Dollar Weather and Climate Disasters." (NOAA, 2023)

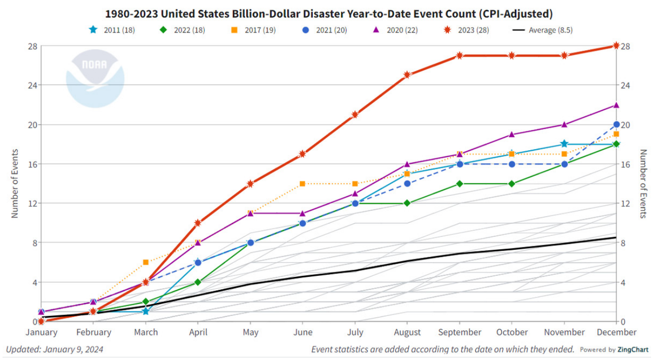

Figure 3.“1980-2023 U.S. Billion-Dollar Disaster Year-to-Date Event Count.” (NOAA, 2024)

Responding to these emergencies can often be dangerous, unpredictable, and highly complex. Moreover, humanitarian efforts can grow in complication if the disaster forms quickly, such as in the case of a fire or flash flood, or if it occurs in a densely populated urban environment or both. In order to adequately address these disasters, many cities employ Emergency Management (EM) processes in some capacity. According to the Federal Emergency Management Agency (FEMA), Emergency Management (EM) is defined as “the managerial function charged with creating the framework within which communities reduce vulnerability to hazards and cope with disasters.” (FEMA, Emergency Management 2022). An example of this framework comes in the form of an Emergency Operations Plan (EOP). An EOP “describes actions to be taken in response to natural, man-made, or national security hazards, detailing the tasks to be performed by specific agencies at projected times and places based on established objectives, assumptions, and assessment of capabilities.” (City of New Bedford 2022). While these plans are often adequately effective, there often exist complications that can weaken the efficacy of the disaster response. These concerns include staffing issues, inefficient deployment of resources, fractured communication, and lapses in hazard identification and reporting.

The resilience evolution of the smart city presents an opportunity to use technology to address these challenges by assisting Emergency Personnel in disaster planning and augmenting the overall effectiveness of disaster responses. One such solution could be through the implementation of a Digital Twin (DT). Specifically, this paper will discuss on the large-scale concept of a Digital Twin City (DTC), its characteristics, advantages, developmental process, and potential role within an Emergency Management Plan (EMP). Utilizing these systematic advantages of a Digital Twin City (DTC) can assist in maintaining the continuity of EM services during multiscale, urban disaster situations and help optimize each of its constituent phases of planning.

EMERGENCY MANAGEMENT

FEMA defines a disaster as “An occurrence of a natural catastrophe, technological accident, or human-caused event that has resulted in severe property damage, deaths, and/or multiple injuries.” (FEMA “Glossary of terms” 2022). As part of their national training program, FEMA identified a list of disasters that can affect a community. To help frame this perspective on disasters in the U.S., a condensed version of this list is below (Wayne, B. 2005).

1. “Damaging Winds,
2. Drought and water shortage,
3. Earthquakes,
4. Extreme heat,
5. Floods and flash floods,
6. Hail,
7. Hurricanes and tropical storms,
8. Landslides & debris flow,
9. Thunderstorms and lighting,
10. Tornadoes,
11. Tsunamis,
12. Wildfire”,
13. building, or structural fire,
14. Winter and ice storms, and
15. Sinkholes

The paper focusses on climate related disasters. Flooding is a coast-to-coast threat to the United States, the discussion narrows down to floods and flash floods that present both a consistent and considerable threat to life and economic loss within urban environments. Effective adaptation of DTT for increasing flash flood risks.

Flooding is the most damaging and dangerous natural disaster in the United States. Within the past decade, floods have contributed to more than $50 billion in damages (NOAA, “Billion-dollar weather and climate disasters” 2022). According to the Department of Homeland Security, “floods inflict more economic damage and loss of life and property than any other natural hazard” (Homeland Security 2023). Flash flooding is especially dangerous as it combines the destructive power of a flood with a swift and powerful surge of water (NSSL 2023). According to the NOAA National Severe Storms Laboratory (NSSL 2023), "Flash floods occur when heavy rainfall exceeds the ability of the ground to absorb it." This type of flooding forms quickly, often within a few hours of excessive rainfall (or other causes). Additionally, these powerful surges often carry a deadly assortment of collected debris, damaging houses and buildings, and posing a significant risk to human life.

Flash flooding presents the most danger to city residents due to the impervious nature of the ground and building surfaces. The danger and complexity of these situations can increase significantly if the area is densely populated, contains insufficient egress, or the drainage systems are not equipped to handle such large amounts of runoff.

A disaster such as flash flooding presents a unique combination of humanitarian and economic challenges to emergency responders. These situations are often complex, time-sensitive, stressful, and unpredictable. They are responsible for tasks such as searching for missing persons, giving life-maintaining aid to affected victims, managing the hazard, and minimizing further damage and injury, among many others. Most cities approach these chaotic situations through the means of an organized plan known as an Emergency Operations Plan (EOP). Alternatively, these are sometimes referred to as an Emergency Management Plan.

An Emergency Operations Plan (EOP) acts as a cycle generally consisting of four main phases: "mitigation, preparedness, response, and recovery." In the event of a disaster, these phases outline specific strategies and procedures that address different stages and aspects of the emergency.

The mitigation phase refers to long-term preventative measures intended to reduce the risk and potency of disasters by identifying potential hazards (FEMA "Hazard Mitigation Planning" 2023). Examples of these mitigative procedures include building codes and zoning requirements (Stlouis, MO 2022). Preparedness refers to "the sequence of actions taken to plan, organize, equip, train, and exercise to build and sustain the capabilities necessary to prevent, protect against, mitigate the effects of, respond to and recover from threats and hazards." (FEMA "Continuity Terms" 2020). Examples of preparedness include mutual aid agreements, disaster education campaigns, and the recruitment and training of personnel and citizens (Stlouis, MO 2022).

The response phase consists of the actions performed immediately before, during, or following an emergency (Stlouis, MO 2022). These efforts focus on saving lives, minimizing damage to infrastructure, and reducing hazardous conditions. Evacuation efforts, providing medical aid, managing emergency shelters, and conducting large-scale urban search and rescue missions are a few of these responsive actions (Stlouis, MO 2022). The last phase is recovery. In this phase, the affected community's physical, social, and economic losses are evaluated, and restorative actions are employed to assist the rebuilding process. (FEMA "Mission Areas and Core Capabilities" 2020). These actions can include cleanup and restoration of damaged infrastructure, emergency housing, and financial rehabilitation (Stlouis, MO 2022).

These four cyclic phases form the fundamental concept of continuity within emergency management. The Federal Emergency Management Agency (FEMA) defines continuity as "The ability to provide uninterrupted critical services, essential functions, and support, while maintaining organizational viability, before, during, and after an event that disrupts normal operations." (FEMA "Continuity Resources" 2022).

Maintaining continuity is crucial when responding to any emergency situation. However, a few challenges can occur before, during, or after a disaster situation that can reduce the effectiveness of a unified response. The first issue is inefficient or delayed hazard reporting due to human error, a system-related malfunction, inadequate training, or a combination of these. The Integrated Public Alert & Warning System is the national system used by FEMA for local alerting that described to provide "authenticated emergency and life-saving information to the public through mobile phones using Wireless Emergency Alerts, to radio and television via the Emergency Alert System, and on the National Oceanic and Atmospheric Administration's Weather Radio." (FEMA "Integrated Public Alert & Warning System" 2022). Many other countries employ similar systems to notify their citizens of potential hazard warnings and the risk levels of their area(s). While these alert systems are typically very beneficial, they can still experience delays, temporary disruptions, or complete system failures that can put many lives and properties at risk.

An example of this happened in late February 2022 in Brisbane, Australia. The region had experienced extreme rainfall, which caused the area's worst flooding in more than a decade. This flooding resulted in the deaths of 13 people and the damage of more than 9,000 homes and businesses (Guardian 2022). While many cities began alerting residents within the next day or two, the Brisbane city council chose not to request emergency alerts to be sent to residents until several days later. Because of this, several residents did not receive emergency warming alerts until well after their homes were inundated.

Training deficiencies within the Brisbane city council were significant factors in this initial delay. A few of the council members were not adequately educated in the processes of the state's emergency alert system. Emergency Services Minister Mark Ryan mentioned that the Brisbane City Council had been offered Alert System training for years but chose not to complete it. (Riga 2022). Once the Brisbane City Council sent their "advice" level request, it was delayed further due to the more critical alert requests from other councils.

At this time, the state government's central emergency alert system experienced a severe malfunction. Due to several factors, such as the backlog of SMS transmissions and alert requests from a multitude of city councils, caused the entire SMS system to be "overloaded." (Guardian 2022). As a result, the system crashed and was down for nearly an hour. For the residents of Brisbane, it took more than 12 hours from the time of request for the first flood alert to be issued. By this point, rainfall conditions and the river's tidal cycle had worsened significantly, and many homes and businesses were already flooded. (Riga 2022).

Another challenge that emergency management (EM) personnel face is the task of Urban Search and Rescue. According to the International Association of Fire Chiefs, Urban Search & Rescue (US&R) is a multi-hazard discipline that involves the location, extrication, and initial medical stabilization of victims trapped or missing because of a man-made or natural disaster. (IAFC 2022). In 2003, the Federal Emergency Management Agency and the National Institute of Justice (NIJ) initiated an effort to identify practical requirements for new and improved technologies and practices that meet both US&R teams and law enforcement needs. Select US&R task force representatives from the United States, and Canada were invited to a workshop to develop these requirements. They were given a series of disaster scenarios to help facilitate discussions and potential solutions. Below is a condensed list of a few of the applicable and recurring requirements that were determined to be high-priority needs: (FEMA, "Identification of Needs" 2004).

1. Improved real-time data access (data pertaining to site conditions, personnel accountability, medical information, etc.)

2. The ability to communicate (transmit signals) through/around obstacles

3. Improved monitoring systems (i.e., atmospheric, biomedical, personnel accountability, etc.) - real-time, portable, multi-function devices that expand on existing detection capabilities

4. Integration/consolidation of functions found in multiple pieces of equipment into a single piece of equipment

5. Reliable non-human, non-canine search and rescue systems - robust systems that combine enhanced canine/human search and rescue capabilities without existing weaknesses (i.e., robots)

6. Standardization of equipment (communication, search, rescue) - equipment that utilizes common platforms, connectors, power supplies, etc.

7. The ability to accurately and non-invasively locate survivors following structural collapse – the ability to "see" through walls, smoke, debris, and obstacles.

Given the complexity of US&R situations, it is beneficial to consider and address these challenges through a practical and integrative solution. The application of Digital Twin Technology presents itself as one such example.

DIGITAL TWINS

A Digital Twin (DT) is "an integrated multi-physical, multiscale probabilistic simulation of a complex object that uses mathematical, physical, and simulative models to accurately reflect a physical object." (Ivanov et al., 2020). In the scope of architecture, this would be an accurate, highly detailed 3D model that receives real-world information through data analysis from various sensor networks, surveillance cameras, drones, Internet of Things (IoT) devices, and other wireless technology. The Internet Engineering Task Force (IETF) defines the Internet of Things (IoT) as "The network of physical objects or "things" embedded with electronics, software, sensors, actuators, and connectivity to enable objects to exchange data with the manufacturer, operator, and/or other connected devices." (IETF "The Internet of Things" 2023). Effective use of a Digital Twin

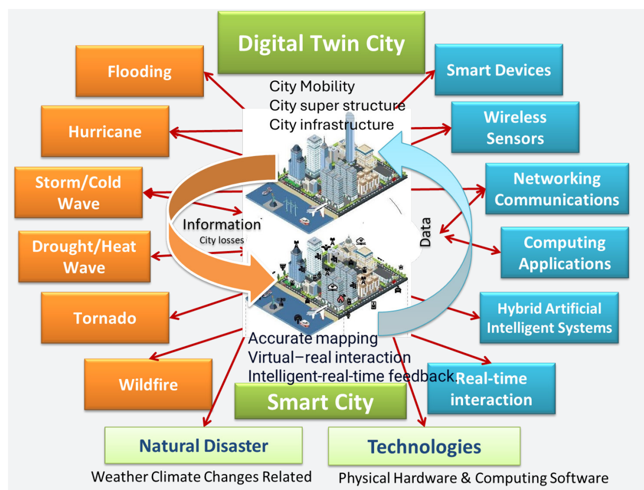

Figure 4. The integration of Digital Twin Technologies into Smart City toward Digital Twin City, regenerated from White G. et al., 2021.

relies upon the continuous delivery of and the ability to process large amounts of data that is collected in near real-time.

A Digital Twin City (DTC), Figure (4), is a complex, interactable, and interconnected system comprised of numerous smaller Digital Twins representing specific functional and developmental aspects of a physical city. Each of these Digital Twins shares a common platform where they can bi-directionally exchange and analyze information such as traffic data, municipal operations, or environmental conditions. In a report from the World Economic Forum, four major characteristics of a "Digital Twin City" (DTC) were identified (Cai et al., 2022). These characteristics included:

1. "Precise mapping of the physical and digital city,

2. Analysis of and insights from the digital city,

3. The intelligent application of insights from the digital city to the physical city, and

4. The virtual-real integration of the digital city and the physical city."

Accurately mapping a city requires the combination of Building Information Modelling (BIM), Geographic Information System (GIS), and Internet of Things (IoT) networks. A primary aspect of this mapping process is the development of a highly detailed 3D model of the city. The Chinese company 51World created one such example. In 2020, they created a complete, virtual copy of the entire city of Shanghai (Weir-McCall 2020). All 3,750 kilometers of it were built within Unreal Engine, which is a 3D creation tool that the company Epic Games developed. In order to model a city of this scale, they used an algorithm that generated 3D geometry through data collected from satellite imagery, building sensors, cameras, and drones. Some of this geometry included buildings, infrastructure, and areas of vegetation (Weir-McCall 2020).

Currently, this city is simply a 3D model. However, the ultimate goal of this project will be to convert this city into a genuine digital twin that is constantly updated with a near-instantaneous stream of sensory data. In addition to presenting a multi-layered, multiscale view of several static municipal operations or entities such as buildings, roads, or water systems, a Digital Twin City (DTC) can also display moving objects as well. The location and movement data of people, vehicles, and public transportation are a few examples. Below is a list of 3 potential examples of constituent "Digital Twins" within a "Digital Twin City" (DTC) (Ivanov et al., 2020).

1. "A digital twin of urban infrastructure, which is an interactive 3D model of buildings, structures, engineering communications, and other urban infrastructure.

2. A digital twin of the transport network, which provides monitoring and forecasting of development of the situation of transport availability, the efficiency of public transport, etc.

3. A digital twin of urban ecology that provides mechanisms for monitoring and forecasting the environmental condition of the urban environment, including the quality of soil, water, air, etc."

The next characteristic revolves around the analysis of the city's collected data. This data included factors such as traffic congestion, noise pollution, water composition, public transportation, urban planning, air temperature, relative humidity, and even the energy consumption levels of each building, among many others (Ivanov et al., 2020). These analyses lead to insights that city planners can use to improve various physical aspects, system operations, and general strategies of the city.

The final phase of a DTC outlined by the World Economic Forum (WEF) is the integration of the virtual and physical city. Processes such as monitoring and decision-making, along with other physical aspects of municipal management, would be remotely operable through the Digital Twin City (DTC) model. WEF describes examples of this fusion of the digital and physical city where "city managers can interact with the physical city on the digital platform interface to search specific entities, select 3D spaces for statistical analysis, change the city layout and simulate changes in various urban indicators such as those relating to congestion and ecology. Through virtual reality, residents can follow distance-learning classes as if actually present in a classroom or laboratory and can embark on travel to distant destinations without actually leaving their homes." (Cai et al., 2022).

INTEGRATIONS

With the growing frequency of disasters, there already exist countless challenges and dangers that Emergency personnel have to plan for, monitor, and respond to. Due to its simulative capabilities, implementing a Digital Twin City (DTC) creates various opportunities to address these dangerous situations within a zero-risk digital environment.

An interesting, real-world example of successfully implementing Digital Twin technology within Emergency Management is the "Digital Twin of Takamatsu city, Japan." Due to a growing risk of riverine flooding caused by localized torrential rain, tsunamis, typhoons, and high tides, Emergency Management officials have recognized three critical issues should a large-scale disaster occur (Kazuhiko & Atsushi 2018). The first issue revolves around determining emergency shelter availability and evaluating associated shelter requirements quickly. The second is the rapid, reliable, and accurate delivery of key emergency information to its citizens. The third issue is the risk of flooding itself. These issues prompted the development of a Digital Twin that monitors and works to prevent emergencies such as floods. This system analyzes data collected from several water- and tide-level sensors and monitors the flood risk in each city district in real time. (Ivanov et al., 2020). These sensors are strategically placed in designated areas outlined in their emergency flood prevention plan (Kazuhiko & Atsushi 2018).

To address the issues of shelter status and availability, this system also collects data provided by smart meters, such as humidity and power usage sensors installed at designated shelters. Utilizing this Digital Twin allows emergency management authorities to visualize the status of shelters that are currently in use, as well as determine the availability of and potential need for additional emergency shelters (Kazuhiko & Atsushi 2018). This information is also provided on a public website, as well as an app that allows staff to register the status of evacuation.

"Before the implementation of this system, there was no way to detect water levels in real-time, so checks were performed on the spot by city staff members. Now, thanks to the introduction of this system, we have been able to provide an environment where early-stage disaster measures (swift provision of accurate information to citizens, an on-the-spot investigation by city staff, etc.) can be readily managed directly from the city hall by live monitoring of the situation in disaster-struck regions." (Kazuhiko & Atsushi 2018).

Of course, the measurable effectiveness and level of assistance that a Digital Twin City can provide depends upon many factors, such as the physical condition of data collection devices (i.e., sensors, cameras, etc.), the strategic placement of these devices, or the density and variety of these data sources within the shared network. However, for the purposes of this paper, we will assume that these advantages result from a fully functioning Digital Twin City (DTC). As previously explained, maintaining the continuity of Emergency services during a disaster situation is extremely important. Implementing a Digital Twin City can help maintain that continuity by assisting the Mitigation, Preparedness, Response, and Recovery phases of an Emergency Operations Plan (EOP). Within the Mitigation phase, examples of existing and potential applications include:

1. Utilizing historical data of similar disasters to foresee potential situational, economic, environmental, humanitarian, and operational developments and challenges that may arise. (Ivanov et al., 2020). This collection and analysis of this information could lead to life-saving decisions or help prepare various countermeasures.

2. Assist in identifying potential hazards that are either ecological or man-made in nature. It could also analyze the hazard's social, locational, and environmental implications and its relationship(s) to the affected community.

3. Simulate disaster situations within the virtual model to assist in the intelligent planning of buildings, water systems, infrastructure, and placement of critical facilities, etc. Simulating these environments can also help identify key evacuation routes, response times based on locational conditions, and efficient deployment of resources, among others.

4. Assist in adequately training Emergency Management personnel and response teams by simulating various disaster scenarios. These simulations can also help administer more effective disaster tests and public safety drills.

5. Centralize and distribute key disaster information, supplies, guidelines, routes, and resources to the public (Kazuhiko & Atsushi, 2018). This centralization of information could help citizens better prepare for disaster situations. Reducing evacuation times is another benefit of this centralization and public visualization of information.

In addition to preventative measures, using a DTC can also have practical applications in more active situations, much like in the example of Takamatsu city, Japan. Within the Response and Recovery phases of an EOP, these applications could include:

1. Automate the delivery of SMS emergency alert notifications based on the intelligent analysis of collected sensory data. This automation can reduce or eliminate the potential for human-caused delays.

2. Analyze visual data provided by surveillance cameras to monitor the congestion levels and flow of vehicular traffic in emergency situations. (Ivanov et al., 2020). This analysis could identify specific routes containing the least traffic to maximize response times and preserve the public's safety.

3. US&R personnel could use the interactive capabilities of a DTC to view a detailed 3D model of a specific building. This model could help familiarize themselves with the layout of the building and optimize the effectiveness and speed of their response. Furthermore, data from surveillance cameras or intelligent, person-detecting devices, such as thermal imaging sensors, could help identify a potential victim's specific level and room location.

4. Monitor the availability of emergency facilities, staffing, and supplies, as well as help, evaluate the need for additional resources (Kazuhiko & Atsushi 2018).

5. Access to up-to-date information, such as new situational or environmental developments, changes in task priorities, or the location data of other responders, could help manage complex emergencies. It can also increase overall inter-organizational communication and personnel accountability.

CONCLUSION

This paper explored the viability of using the Digital Twin technology within the context of Emergency Management. A Digital Twin City (DTC) can be used as a helpful decision-making tool for city personnel to strengthen the continuity of emergency management before, during, and following a disaster situation. Its intrinsic advantages allow for a faster, more effective flow of information. Its simulative capabilities can provide key insights to determine the potential challenges or opportunities within any specified scenario. Furthermore, the virtual nature of this technology ensures that these probabilistic investigations can be completed with no risk to the lives of citizens or personnel. By applying its systemic benefits to Emergency Management, Digital Twin technology exists as a promising solution to make our cities smarter, safer, and more sustainable for future generations.

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