Using Digital Twins of a Smart City for Disaster Management

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ABSTRACT

Digital twins, advanced virtual models replicating physical objects or systems, are becoming integral to smart city solutions, particularly in disaster management. By integrating real-time data from sensors and Internet of Things (IoT) devices, digital twins simulate and analyze physical entities' behavior and performance, providing real-time monitoring, predictive insights, and operational optimization. This study explores the application of digital twins in smart city disaster management, focusing on key solution components such as sensors, data integration, simulation engines, and visualization interfaces. It highlights the top use cases, including supply chain optimization, public transit management, and the performance of experiments. Additionally, industry examples, such as DHL's supply chain twin and Singapore's digital twin for urban planning, demonstrate the value of this technology in disaster resilience. The integration of digital twins enables smart cities to better manage disasters, optimize resources, and improve public safety, ultimately enhancing urban sustainability.

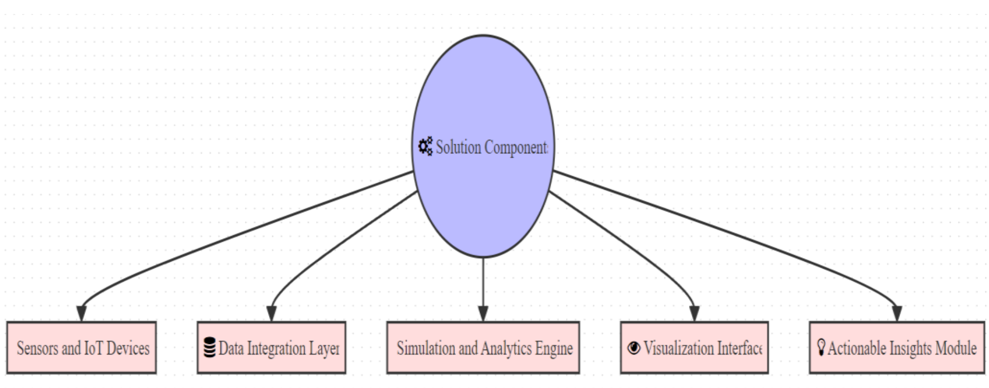
Keywords: Digital twins, smart city, disaster management, IoT, real-time monitoring, predictive analytics, supply chain optimization, public transit management, urban resilience, simulation models.

1. INTRODUCTION

A digital twin is a sophisticated virtual model designed to replicate a physical object, system, or process with remarkable accuracy. It is created by integrating real-time data from various sources, such as sensors and Internet of Things (IoT) devices, which continuously provide information about the physical entity to the digital model. The primary purpose of a digital twin is to simulate and analyze the behavior and performance of its physical counterpart in real-time, offering a detailed examination of how the object or system operates under different conditions—insights that traditional monitoring methods cannot readily provide (Lu et al., 2020). Through digital twins, organizations can monitor the real-time status and performance of physical assets or processes, predict future behavior and potential issues by running simulations, and optimize operations by analyzing data to enhance efficiency and reduce costs (Lu et al., 2020). This dynamic interaction between the physical and virtual worlds enables a comprehensive view of the physical entity's state, supporting more informed decision-making, improving operational efficiency, and driving innovative solutions to complex challenges.

2. Solution Components and Reference Architecture

2.1. Solution Components



Sensors and IoT Devices
Function: Sensors and IoT devices are crucial for collecting real-time data from a physical environment. These devices monitor various parameters such as traffic flow, weather conditions, and structural health, and send continuous data to the digital twin model. This data is essential for accurately reflecting the current state of the physical object or system and for updating the virtual model in real-time (Tao et al., 2018).
Examples Traffic cameras, weather stations, and building sensors.

Data Integration Layer
This layer is responsible for aggregating and processing the data from multiple sources. This ensures that data from different sensors and systems are seamlessly combined while maintaining accuracy and consistency. The data integration layer plays a vital role in transforming raw data into a usable format for analysis and simulation (Nils Kuever, 2018).
Components: Data aggregators, middleware, and data preprocessing tools/services running in Cloud.

Simulation and Analytics Engine
The simulation and analytics engine analyzes integrated data to create detailed simulations of the physical object or system. It uses various algorithms and models to predict future behaviors, identify potential issues, and assess different scenarios. This engine enables predictive maintenance, optimization, and informed decision-making by providing insights into how the system might perform under various conditions (Grieves, 2015).
Components: Computational models, machine learning algorithms, and simulation software.

Visualization Interface
The visualization interface provides a graphical representation of the data and simulations. It allows users to interact with the digital twin, view real-time data, and explore different scenarios. Effective visualization helps users understand complex data and simulations, making it easier to identify trends, patterns, and anomalies (Glaessgen & Stargel, 2012).
Components: Dashboards, graphical user interfaces (GUIs), and 3D models.

Actionable Insights Module
The digital twin system for disaster management operates through several key processes, each of which plays a critical role in ensuring the accurate monitoring, analysis, and management of real-world environments. First, data collection takes place through various sensors and IoT devices that capture real-time information from the physical environment, such as weather conditions, traffic patterns, and infrastructure health. This data serves as the foundation for building the digital twin model.
Once collected, the data moves to the data management phase, where it is processed, stored, and managed to ensure its quality and reliability. This involves tasks, such as data cleaning, integration, and validation, to create a unified and accurate dataset. The validated data is then used in the modeling and simulation stage, where the digital twin model is created and continuously updated. Simulations are run to reflect the behavior of the physical system and predict future scenarios, such as the potential impact of a natural disaster.
Based on these simulations, the system provides decision support by generating actionable insights. These insights help users make informed decisions by offering recommendations, generating alerts, and suggesting actions such as triggering automated responses to mitigate potential risks. For instance, the system may alert maintenance teams or adjust system parameters to prevent issues (Nils Kuever, 2018).
Finally, the user interaction component enables users to engage with the digital twin through a visualization interface. This interface allows users to access real-time data, explore different simulations, and make decisions based on actionable insights. The architecture of the system ensures that the digital twin offers an accurate, real-time reflection of the physical entities it represents, thereby facilitating effective monitoring, analysis, and disaster management.

2.2. Reference architecture of a Smart City

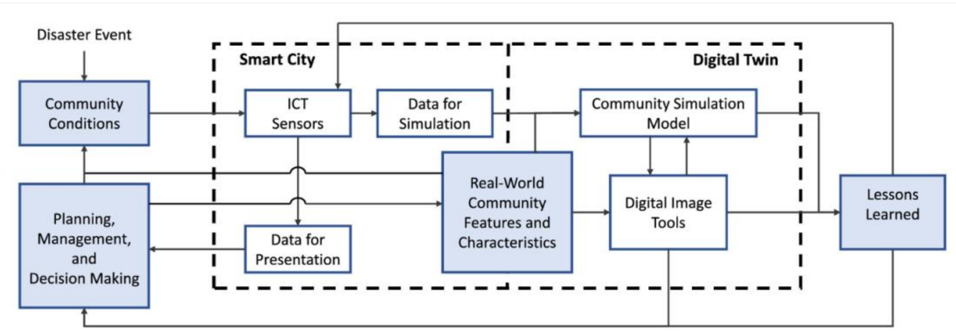


Figure 1: Community disaster management model with a smart city digital twin. (Source: Ford & Wolf, 2020)

This diagram illustrates the interaction between a smart city and its digital twin in the context of disaster management. When a disaster occurs, it triggers the need for planning and decision-making, relying on real-time community conditions. These conditions are captured through sensors and IoT devices within the smart city, which feed data, such as traffic flow and weather information, into the system. This data is then used to update the community simulation model in the digital twin. Once processed, the data is presented for analysis through digital tools, enabling simulations and visualizations that provide valuable insights into potential disaster scenarios and response strategies. The lessons learned from these simulations are used to refine future decision-making and improve preparedness. The entire system operates in an iterative cycle, continuously integrating real-world data, simulations, and insights to enhance the disaster management strategies over time.

3. Importance of Digital Twins

3.1. Driving Innovation and Agility

Digital twins play a critical role in fostering faster innovation, agility, and responsiveness across various sectors. By providing a virtual representation of physical systems, they allow for rapid testing, iteration, and optimization of new ideas. This ability to simulate changes in real time enhances an organization's capacity to adapt to evolving challenges and market demand. In manufacturing, digital twins drive excellence through virtual factory replication, enabling organizations to innovate more quickly while minimizing risks (Grieves, 2015). For example, Siemens uses digital twins to optimize their manufacturing plants, increasing efficiency and reducing errors during the production process. Additionally, automotive companies such as Tesla implement digital twins for vehicle design and performance testing, speeding up the development of new models(Grieves, 2015).

3.2. Transformative Impact:

The transformative nature of digital twins lies in their capacity to optimize processes, enhance operational efficiency, and enable predictive maintenance. Industries, such as manufacturing, healthcare, and urban planning, benefit significantly from automating routine tasks, identifying inefficiencies, and predicting potential system failures before they occur. For instance, in the energy sector, companies such as GE use digital twins to manage power plants, enhancing efficiency and predicting equipment failure. Smart manufacturing exemplifies this transformation by improving production workflows and reducing downtime, fundamentally altering how industries operate (Tao et al., 2018).

Healthcare is another domain that is significantly affected from digital twins. Hospitals and medical equipment manufacturers utilize digital twins for personalized patient care, predicting disease progression, and optimizing medical device performance. Philips, for example, has developed digital twin solutions for medical imaging systems, enabling predictive maintenance and enhancing the operational efficiency in hospitals. Digital twins of human organs, such as heart or lung simulations, offer physicians the ability to test different treatments virtually before applying them to patients

3.3. Informed Action and Control

Digital twins support informed decision-making and control in both industrial applications and emergency management. By continuously gathering data from sensors and IoT devices, these virtual models provide real-time insights that can help operators predict and mitigate issues. This proactive approach to system management enhances the ability to respond more effectively to emergencies.

NASA and the U.S. Air Force use digital twin technology to enhance control over complex systems and improve decision-making in critical missions. NASA employs digital twins for spacecraft and rovers, such as the Mars Curiosity Rover, to simulate real-world conditions and test scenarios, predict system failures, optimizing mission performance, and preventing malfunctions. The U.S. Air Force uses digital twins for aircraft maintenance, allowing real-time monitoring and predictive maintenance to reduce downtime and ensure mission readiness. This technology helps both organizations make better decisions and improve operational efficiency in high-stakes environments (Glaessgen and Stargel, 2012).

3.4. Market Size and Future Growth

The digital twin market is experiencing rapid growth. According to industry reports, the global digital twin market was valued at approximately USD 6.9 billion in 2023 and is projected to reach USD 73.5 billion by 2030, growing at a compound annual growth rate (CAGR) of 40.6% (Matterport, 2024). This growth is fueled by increasing adoption across various sectors such as manufacturing, healthcare, automotive, and smart cities. In particular, the healthcare industry is expected to experience substantial growth owing to the rising demand for personalized medicine and predictive analytics, further reinforcing the value of digital twins in driving innovation and operational efficiency.

3.5. Adoption and Productivity

The rapid adoption of digital twins across industries underscores their pivotal role in improving productivity, operational efficiency, and competitive advantage. From construction to logistics, organizations leverage digital twins to streamline operations, reduce costs, and stay ahead in a competitive landscape. Digital twins have a significant impact on construction management, where they help optimize workflows and resource allocation, resulting in enhanced project delivery and efficiency (Jiang et al, 2021).

3.6. Advantages and Disadvantages

Digital twins offer numerous advantages, including enhanced operational efficiency, predictive maintenance capabilities, improved decision making, and long-term cost savings. These benefits make them a highly attractive solution for industries seeking to optimize their processes. However, there are some challenges. High initial implementation costs, the complexity of integrating digital twins with existing systems, and concerns over data security and privacy can pose significant barriers to widespread adoption.

4. Smart City Solutions

4.1. Definition of a Smart City

A smart city is an urban area that integrates digital technologies to improve the efficiency of city operations, services, and resource management, ultimately enhancing the quality of life for its residents (Dameri & Dameri, 2017). Using Internet of Things (IoT) devices, sensors, and data analytics, smart cities can monitor and manage urban infrastructure, traffic systems, energy consumption, and public services more effectively. This enables cities to become more sustainable, resilient, and responsive to the needs of their citizens.

Governments worldwide are increasingly investing in and building smart cities to address urban challenges such as population growth, environmental sustainability, and infrastructure pressure. One key reason for this investment is the ability of smart cities to improve resource management and reduce operational costs, thereby making urban environments more efficient and less wasteful. For example, smart grids optimize energy consumption, whereas smart traffic systems help reduce congestion and emissions.

Additionally, governments view smart cities as a critical response to climate change, where digital technologies can aid in reducing carbon footprint and fostering green development. By building smart cities, governments aim to enhance public safety, improve healthcare services through connected devices, and create smarter transportation networks that enhance mobility. Moreover, investment in smart cities is seen as an engine for economic growth, attracting innovation, creating jobs, and fostering a competitive edge on the global stage. Consequently, smart cities not only improve the lives of their residents, but also contribute to broader economic and environmental goals.

4.2. Benefits of Digital Twins for Smart Cities

Digital twins provide numerous benefits to smart cities by optimizing city operations, managing resources efficiently, and enhancing public services. By creating virtual replicas of physical urban environments, cities can simulate and predict the behavior of infrastructure, traffic systems, and public services under different scenarios (Ketzler et al, 2020). This allows city planners to optimize resource use, reduce energy consumption, and enhance the reliability of essential services, such as water supply, transportation, and healthcare. Furthermore, digital twins enable predictive maintenance of urban assets, prevent breakdowns before they occur, and facilitate more efficient management of city resources.

4.3. Leveraging Digital Twins for Disaster Management

Digital twins are particularly valuable in disaster management for smart cities as theyprovide real-time insights and predictions to minimize the impact of natural or man-made disasters.

Telemetry Integration

Digital twins can integrate data from various sources such as traffic systems, population density metrics, water levels, and disaster progression information. This allows for a comprehensive understanding of how a disaster is likely to affect different parts of acity (Brucherseifer et al., 2021). For instance, data on flood levels, road traffic, and population distribution can be used to predict the areas most vulnerable to flooding and allocate resources accordingly.

Real-time Data and Response

One of the key advantages of using digital twins in disaster management is the ability to monitor real-time data. During emergencies, real-time monitoring of environmental and urban data can help guide citizens to safer locations, while city officials can coordinate response efforts more efficiently (Brucherseifer et al., 2021). For example, during a flood or earthquake, digital twins can simulate a disaster's progression and offer insights into the safest evacuation routes, minimizing the impact of the disaster on human lives and infrastructure.

By combining real-time data, simulations, and predictive analytics, digital twins empower cities to respond swiftly to disasters, protect critical infrastructure, and ensure public safety. These capabilities make digital twins an essential component of the smart city ecosystem, particularly in the context of disaster resilience and urban sustainability.

5. Top Use Cases for Digital Twins in Smart Cities for Disaster Management:

5.1. Supply Chain Optimization

Digital twins enhance the visibility and efficiency ofsupply chain management, that are crucial during disasters. They simulate real-time disruptions such as road closures, environmental factors, and resource availability, allowing businesses to reroute supplies or adjust inventories.

In 2019, DHL developed a digital twin for its supply chain management system. This digital model provides real-time insights into logistics, allowing quick adjustments during natural disasters, such as hurricanes, where road networks are impacted (Galea-Pace, 2020).

5.2. Public Transit Management

Digital twins optimize public transportation systems by analyzing traffic patterns, ridership data, and potential disruptions. These simulations enable better planning, improved safety, and effective response strategies during disasters.

In 2018, Singapore implemented a digital twin of its public transportation system to monitor traffic and simulate evacuation routes during emergencies (Yang & Kim, 2021). The digital twin enabled the seamless rerouting of buses and trains in response to road accidents and flooding.

5.3. Performance of Experiments

Digital twins can test and refine disaster response systems by simulating various disaster scenarios. This allows authorities to plan resource allocation, evacuation routes, and emergency procedures with minimal risk.

In 2020, the city of Helsinki used a digital twin to simulate extreme weather events, particularly focusing on snowstorms and their impact on infrastructure(Mervi Hämäläinen, 2021). These experiments helped optimize snow clearing processes and predict traffic disruptions.

5.4. Industry Examples

Thyssenkrupp, Willow, and Microsoft Collaboration

Thyssenkrupp, in collaboration with Willow and Microsoft, created a digital twin of its Innovations Test Tower before 2022(See, 2019). This digital model allowed the company to monitor system performance and pre-emptively address disruptions, including those that could arise during natural disasters.

The digital twin of Thyssenkrupp’s Innovation Test Tower was powered by IoT sensors strategically placed throughout the structure to collect real-time data on key performance metrics. These sensors monitored the temperature, pressure, vibration, and system integrity, providing crucial insights into the

operational health of the tower. Microsoft Azure served as the backbone for processing and storing the sensor data, with the Azure IoT Hub enabling the integration of IoT devices and Azure Digital Twins, supporting the creation of detailed digital models of the physical tower.
To further enhance its capabilities, the system utilized Azure AI and machine learning models to analyze the collected data. This allowed for the identification of anomalies and prediction of potential disruptions, such as those triggered by extreme weather conditions or structural stress. Visualization and real-time monitoring of the tower status were made possible by Willow, a digital twin platform that created a 3D digital model of the tower. This model can simulate disaster scenarios, including earthquakes and high winds, to evaluate the response of the tower and enable proactive maintenance.
The predictive analytics capabilities of the digital twin played a critical role in enabling pre-emptive maintenance, allowing Thyssenkrupp to detect issues before they escalated into significant problems. In the case of natural disasters, the digital twin can simulate emergency situations, aiding in faster response times and improving recovery planning to minimize disruptions.

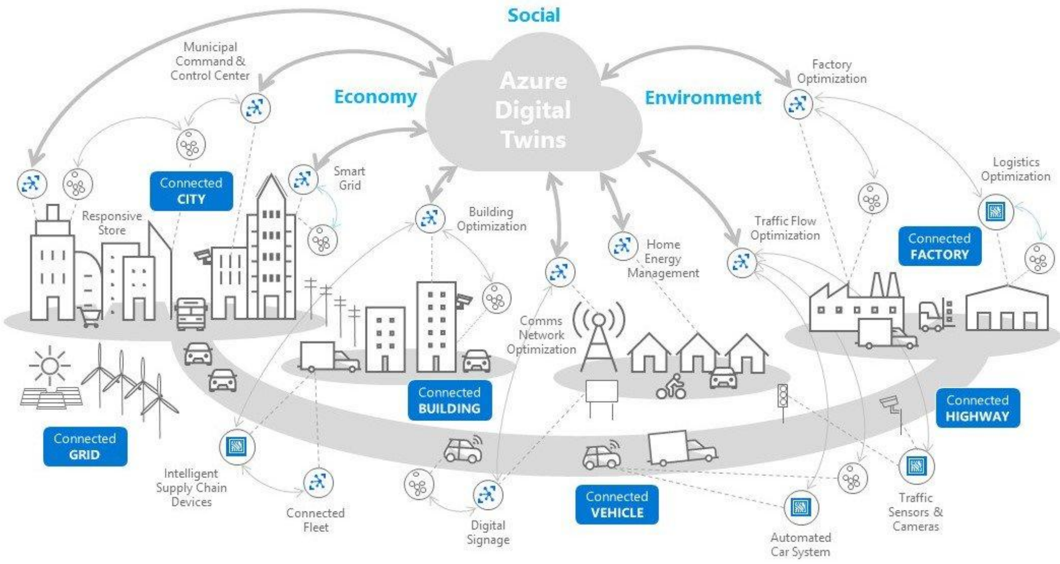


Figure 2: Azure Digital Twins Platform, Source: (Azure, 2018)

The image illustrates the Azure Digital Twins platform and its integration with various connected systems across different sectors including buildings, cities, grids, vehicles, highways, and factories. This highlights how Azure Digital Twins can optimize operations in areas such as traffic flow, energy management, logistics, and factory production by connecting physical assets with a digital twin model. This allows for better planning, monitoring, and predictive maintenance, ultimately improving the efficiency in environments such as smart cities, connected factories, and transportation networks.
This aligns with Thyssenkrupp's collaboration with Willow and Microsoft in using a digital twin for their Innovation Test Tower. By integrating IoT sensors, Azure cloud infrastructure, and predictive analytics, the digital twin helps monitor and manage tower performance while also enabling simulations for disaster management and pre-emptive maintenance.

Virtual Singapore: Digital Twin for Urban Planning
Launched in 2018, the Virtual Singapore project used a digital twin for disaster management, urban planning, and improving public services(Doğan et al., 2021). It simulated scenarios such as building collapses or floods, helping the city refine its emergency response strategies.
The foundation of Virtual Singapore's digital twin was a 3D geospatial model that accurately represented the entire city. This model was developed using high-resolution satellite imagery, LiDAR scanning, and other advanced geospatial data collection technologies. The platform integrated multiple data sources, including real-time traffic information, environmental data, building infrastructure details, and population density statistics. These inputs were sourced from government systems, private sector contributions, and public IoT devices scattered throughout the city.
A key feature of Virtual Singapore was its use of simulation engines to model various disaster scenarios. For example, it could simulate building collapse or flooding in specific areas and predict how such events would affect the surrounding environment and public services. This capability allowed city planners to

anticipate risks and prepare effective response strategies. The digital twin was hosted on a cloud infrastructure that enabled real-time data processing and storage. Through the use of advanced analytics powered by machine learning algorithms, city planners could analyze disaster scenarios and optimize their responses based on historical data.
Additionally, the platform provided collaboration and decision support tools, allowing government agencies and other stakeholders to work together in real-time. These tools delivered insights into potential vulnerabilities and supported informed decision-making in urban planning and disaster management. The system facilitated fast scenario testing, helping officials pre-emptively identify areas of concern and efficiently allocate resources. By leveraging the vast amount of data collected through the digital twin, Singapore was able to enhance public services, optimize traffic management, and manage public health responses in real-time.

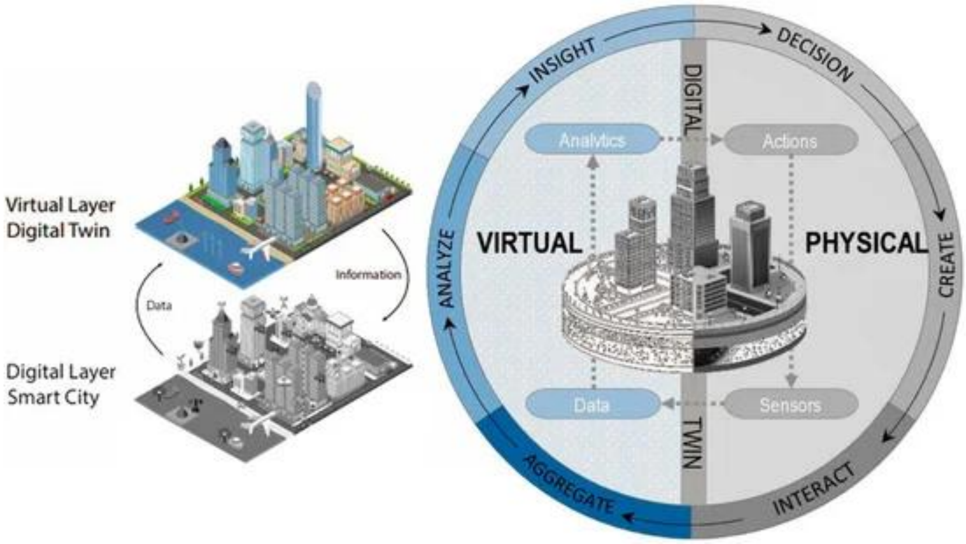


Figure 3: Digital Twin of Smart City, Source: (Caprari et al., 2022)

The image illustrates the concept of a digital twin for smart city planning, showing two layers: a physical (real-world) layer and a virtual (digital) layer. On the left, a diagram shows how data from the physical city is captured by sensors and processed in the virtual layer to create a digital twin that provides real-time information and insights. The circular diagram on the right highlights the process of using the digital twin for urban management, where data is analyzed and aggregated, leading to actionable insights that influence physical actions in the real world.
This is closely related to Virtual Singapore's project, which uses a digital twin for urban planning and disaster management. By simulating real-world scenarios, such as building collapses or floods, the platform helps enhance public service efficiency and refine emergency response strategies.

6. CONCLUSION

Digital twins have become indispensable in smart city disaster management by providing real-time insights, predictive analytics, and enhanced operational efficiency. By mirroring real-world environments through comprehensive data integration from IoT devices and sensors, digital twins enable city planners and emergency services to better anticipate, manage, and mitigate the effects of disasters. Their capacity to simulate various disaster scenarios allows for informed decision-making andimproves disaster preparedness, response, and recovery efforts. Digital twins offer powerful tools for minimizing the impact of natural and man-made disasters, such as optimizing supply chains, managing public transit, and simulating emergency response.
In addition to disaster management, digital twins help optimize broader urban operations by allowing cities to monitor infrastructure, transportation, and public services in realtime. These benefits extend beyond emergencies andcontribute to the overall sustainability and resilience of urban environments. Predictive maintenance and resource allocation improvements result in cost savings, energy efficiency, and prevention of breakdowns before they occur.
Industry examples such as DHL's supply chain twin, Singapore's digital twin for public transit, and Thyssenkrupp's Innovations Test Tower collaboration with Willow and Microsoft underscore the real-world value of digital twins in disaster management. These examples illustrate how digital twins can be

tailored to specific sectors, helping organizations and cities to optimize their responses to disaster scenarios and ensure operational continuity.

As cities continue to grow and face increasingly complex challenges from climate change, natural disasters, and urbanization, digital twins offer a scalable and efficient solution for ensuring public safety and urban sustainability. Their ability to integrate vast amounts of real-time data, run simulations, and provide actionable insights positions them as critical tools for building smarter, safer, and more resilient cities in the future.
In summary, the integration of digital twins into smart city ecosystems marks a significant step forward in urban planning and disaster management, offering unprecedented capabilities to anticipate, respond to, and recover from disasters, thereby improving public safety and urban resilience.

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