DCU BUSINESS SCHOOL

Digital Twins for Impact (DT4I): Using digital twins to deliver effective risk and emergency management

Professor Caroline McMullan
Romal Thakkar

Digital Twins for Impact (DT4I):

Using Digital Twins to Deliver Effective Risk and Emergency Management

Published by:

Digital Twins for Impact (DT4I),

DCU Business School,

Dublin City University,

Dublin, Ireland.

www.business.dcu.ie

ISBN: 978-1-9193584-4-4

Edition: First Edition

Publication Format: eBook (PDF)

Authors: Prof. Caroline McMullan and Romal Thakkar

Contents

Table of Figures

List of Abbreviations

AI – Artificial intelligence

AR – Augmented Reality

BIM – Building Information Model

DT – Digital Twin

DTSC – Digital Twin Smart City

EM – Emergency Management

GIS – Geographic Information System

GPS – Global Positioning System

IoT – Internet of Things

ML – Machine Learning

MR – Mixed Reality

UAVs – Unmanned Aerial Vehicles

VR – Virtual Reality

XR – Extended Reality

1.0 Introduction

The Digital Twin (DT) concept was first proposed by Dr Michael Grieves in 2003, within the context of Product Lifecycle Management. He described DT as consisting of three main components:

(1) The physical product in real space
(2) The virtual product in virtual space
(3) The data and information that tie the virtual and physical products together (Grieves, 2014).

While the term was coined in the early 2000s, the underlying concept can be traced back to the 1960s during the NASA Apollo missions (Rosen *et al.*, 2015). Although the term Digital Twin was not used at the time, the foundational principles behind the concept were applied. NASA engineers maintained exact physical and simulated counterparts of spacecraft systems on Earth, using real-time telemetry data to mirror conditions aboard the spacecraft. These ground-based replicas enabled engineers to monitor performance, run simulations, and develop solutions to in-flight problems; most notably during the Apollo 13 mission. Rosen *et al.* (2015) retrospectively identify this practice as an early example of digital twin thinking, highlighting its conceptual similarity to modern DT implementations, even though the terminology and digital infrastructure were not yet in place.

A DT can be defined as a digital replica or representation of a physical object or asset, such as a service, system, object or process, in the digital world. A DT mirrors many of the properties and attributes of its physical counterpart, enabling accurate modelling and simulation. This capability supports testing, scenario planning, and performance optimisation, thereby enhancing decision-making, effectiveness, efficiency, safety, and risk management.

1.1 Context

Digital Twins (DTs) are widely used across various sectors, each leveraging their capabilities for enhanced modelling, monitoring, and decision-making. Common applications include:

- **Manufacturing**: to replicate and optimise product lifecycles, support production system maintenance, and prevent failures;
- **Construction**: for the safe and efficient management of mega structures such as offshore drilling platforms and high-rise buildings;
- **Energy**: to ensure the safe and effective operation of turbines, wind farms, and power generation facilities;
- **Automotive**: used during design and production phases to enhance vehicle performance, engine efficiency, and manufacturing processes;
- **Science and Public Management**: including applications such as climate change monitoring and the modelling of response strategies;
- **Healthcare**: to simulate medical conditions for diagnosis, treatment planning, and medical training;
- **Aviation**: simulating jet engine production and manufacturing, enhancing maintenance planning, and the safe and efficient operation of airports;
- **Urban and City Planning**: developing DTs of entire cities or districts to support smart city initiatives, urban development, and infrastructure planning.

Within the context of manufacturing, the DT is not just a theoretical concept, but also a practical tool. It is a digital substitute for a real object composed of several models (multi-physical, behavioural, etc.) and data exchange functions, creating intelligent gadgets that act in the nucleus of IoT and IoS (Juarez, Botti and Giret, 2021).

Within the context of an organisation, a DT is a digital representation of a physical object, person, or process, contextualised in a digital version of its environment. DTs can help an organisation simulate real situations and their outcomes, ultimately allowing it to make better decisions (McKinsey, 2023).

Within all contexts, the DT is a virtual representation of an object or system designed to reflect a physical object accurately. It spans the object's lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help make decisions (IBM, 2022). It may use real-time data sent from sensors on the object to simulate behaviours and monitor operations (Amazon Web Services, 2024).

1.2 Digital Twin use in Risk and Emergency Management

DTs are powerful tools for risk and emergency or disaster management in, for example, smart cities, airports, seaports, and manufacturing sites. They may be used at each phase of systematic emergency management as outlined in **Figure 1**.

Figure 1: The Five-Stage Paradigm of Emergency Management (MEM, 2025)

DTs may be used to prepare a variety of disaster scenarios, which will assist with the training and exercising of key actors, including the emergency services (Ariyachandra and Wedawatta, 2023). They can also be used to detect early warning signs that an incident, emergency, or disaster is likely to occur. During such a crisis, they may be used to monitor the evolving situation and to test response strategies. More generally, DTs can assist in building resilience in smart cities. By integrating real-time monitoring, predictive analytics, and testing, they support the full emergency management lifecycle (Fan *et al.*, 2019).

1.3 DT Technologies

DTs utilise a range of technologies to create and maintain virtual replicas and real-time information flow. These technologies work together to enable continuous monitoring, analysis, and simulation. Key technologies include (see **Figure 2**):

- **Internet of Things (IoT)**: Sensors embedded in physical assets capture real-time data (temperature, location, ambient light, status, etc.), enabling continuous monitoring. This constant data stream ensures the digital replica accurately reflects the current state and behaviour of the physical object.
- **Artificial Intelligence (AI)**: AI processes both real-time and historical data to identify patterns, detect anomalies, and predict outcomes. It enables automation and provides insights by highlighting significant trends and changes.
- **Cloud Computing**: Cloud platforms store the large volumes of data generated by sensors and other sources. This data is accessible from any location, at any time, facilitating seamless updates, collaboration, and scalability.
- **Extended Reality (XR)**: XR, which encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), provides immersive and interactive visualisation and experiences of Digital Twins (DTs). These technologies enable the exploration and manipulation of digital representations in various simulated or real-world environments.
- **Unmanned Aerial Vehicles (UAVs)**: Commonly known as drones, UAVs are widely used for aerial data capture and play a critical role in constructing initial 3D models. Equipped with high-definition cameras, advanced sensors, and GPS, they facilitate rapid and accurate capture of spatial and environmental data.

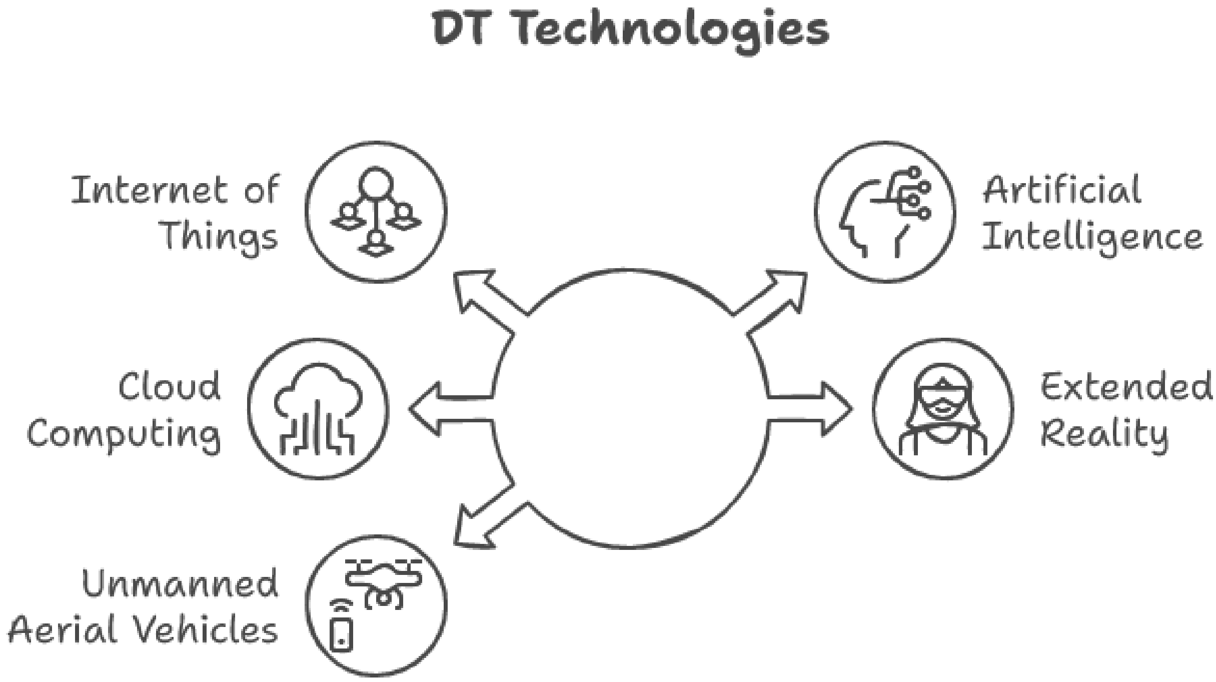

Figure 2: Key Technologies used in DTs

2.0 Literature Review: Use of Digital Twins in Risk and Emergency Management

2.1 Search Strategy

A systematic literature review (SLR) was conducted using Google Scholar, an academic search engine. An advanced search was carried out using the *allintitle* search string: "digital twin" AND (risk OR crisis OR disaster OR emergency). This search, conducted on 3rd September 2024 and excluding citations, returned 61 results. Accordingly, 61 papers were initially identified from the Google Scholar database (as shown in Fig. 3).

Initial screening involved the removal of papers based on the following exclusion criteria:

- Not written in English
- Inaccessible (e.g., behind paywalls or broken links)
- Duplicates across search results

After applying these criteria, 48 papers were excluded, leaving 13 relevant papers from the Google Scholar search.

2.2 Additional Sources

To ensure completeness, a supplementary search was conducted using other academic sources, including grey literature and references cited within the initially selected papers. This process resulted in the identification of 18 additional relevant records.

2.3 Final Selection

In total, 31 papers were included in the final review set. The selection process is illustrated in **Figure 3**.

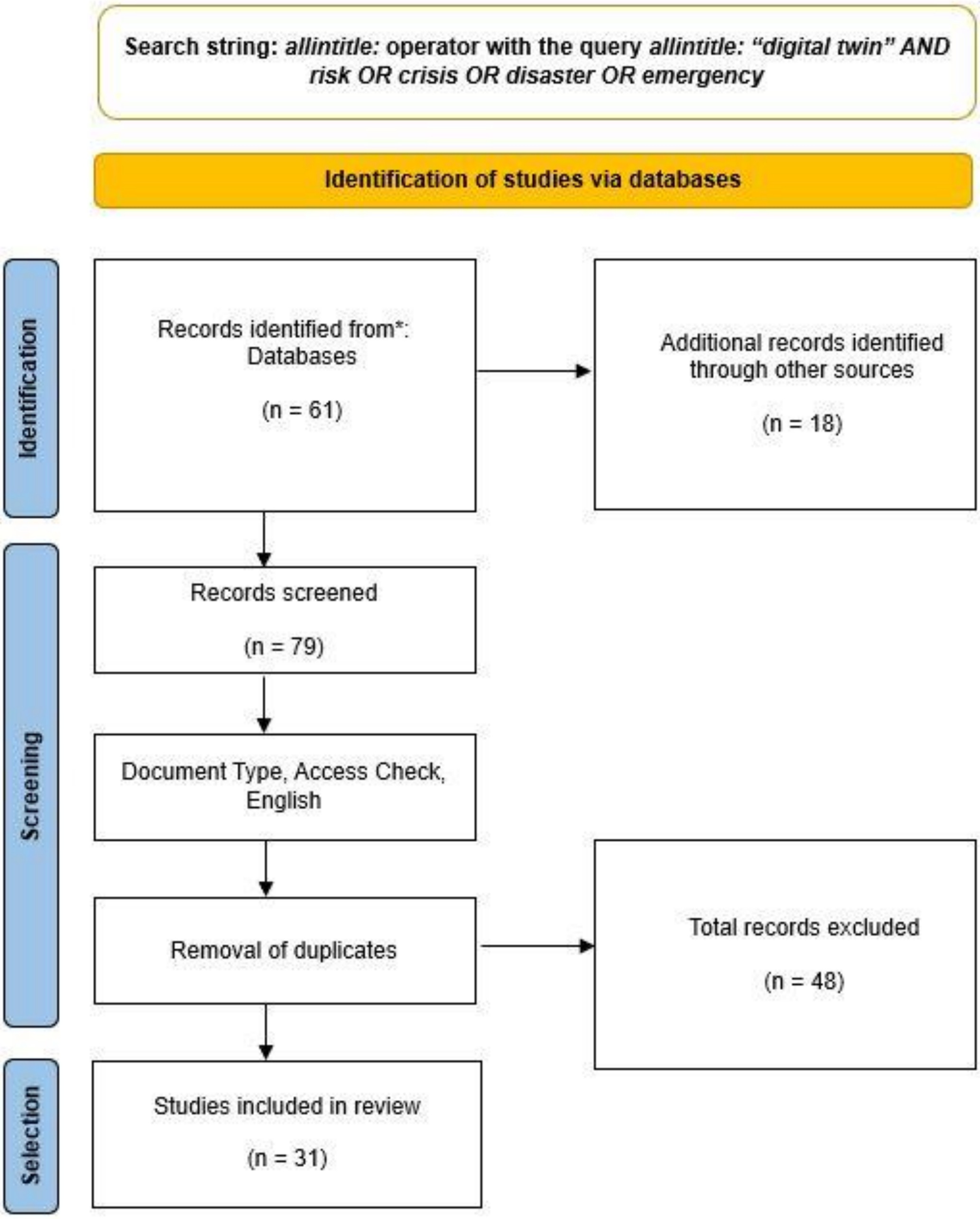

Figure 3: SLR Flow Diagram - adapted from PRISMA

2.4 Overview of Literature Review

The key themes emerging from the literature review are summarised in the mind map below, see **Figure 4**.

Figure 4: Mind Map Depicting Key Topics in Literature Review

Digital Twins (DT) for risk, emergency, crisis, and disaster management can be described as the process of mitigating the effects of risks, as well as planning and preparedness for crises, emergencies and disasters using the digital twin technology. Digital twins are emerging as a powerful tool for risk and emergency management.

Cheng, Hou and Xu (2023) examined the use of digital twin technology within the context of emergency management of civil infrastructure (EMCI) and proposed a comprehensive framework integrating DTs into the four phases of emergency management: mitigation, preparedness, response, and recovery. The framework illustrates how DTs reinforce life-cycle planning for mitigation, enhance decision-making and strategic planning during preparedness, enable resource optimisation and real-time assessment during response, and support collaborative learning and evaluation in the recovery phase. The authors also identify key enabling technologies for implementing DTs in EMCI: Unmanned Aerial Vehicles (UAVs) for collecting data from affected areas, and Computer Vision combined with Deep Learning for automated monitoring and damage assessment based on the UAV-acquired data. Additionally, they highlight emerging trends, including the acceleration of point cloud-to-BIM conversion through automated methods and machine learning algorithms, the use of knowledge graphs to facilitate rapid extraction of critical information during emergencies, and the growing emphasis on data quality and cybersecurity in smart city and infrastructure contexts.

Fan *et al.* (2019) proposed a Disaster City Digital Twin paradigm, which integrates artificial intelligence (AI), multi-source data sensing, and analytics to enhance situation assessment, stakeholder coordination, and decision making in disaster management.

Yu and He (2022) highlighted DT technology as a promising solution for multi-stage infrastructure management and proposed the development of DT-driven Intelligent Disaster Prevention and Mitigation for Infrastructure (IDPMI). Similarly, Kaewunruen *et al.* (2021) underscored the increasing adoption of DTs in the construction industry, particularly for enabling risk-based inspections and proactive maintenance of bridge infrastructure exposed to extreme weather conditions.

Ham and Kim (2020) proposed a framework to enhance urban DTs by integrating crowdsourced visual data into 3D virtual city models. This framework was proposed to enhance disaster response by providing better visibility of hazards and risks, as well as interactions with cities, thereby aiding in infrastructure management and scenario testing for extreme weather events. Similarly, Dogan, Sahin, and Enis Karaarslan (2021) also proposed a digital twin-based disaster management system (DT-DMS) that can be used to allow cities to simulate and prepare for disaster scenarios, particularly earthquakes, in order to optimise disaster response and rescue operations.

Lagap and Ghaffarian (2024) explored the potential of DTs in post-disaster risk management and proposed a digital post-disaster risk management twinning (DPRMT) framework to improve disaster response, resource allocation, and scenario testing. The proposed framework consists of six major components:

1. entities at risk;
2. data collection and pre-processing;
3. data processing;
4. digital modelling;
5. information decoding;
6. user interaction and application.

The first step involves identifying key entities vulnerable to disaster impacts, including critical infrastructure, human lives, and social systems. The second step involves collecting and pre-processing data related to these entities across all phases of the disaster, including before, during, and after the event. In the third step, this data is prepared for digital modelling using a range of techniques, including artificial intelligence (AI), machine learning (ML), statistical analysis, and data validation. The fourth step focuses on creating digital models of the affected entities. This may involve AI-driven modelling, Building Information Modelling (BIM), socio-economic modelling, physical modelling, and others. In the fifth step, these models and datasets are analysed and visualised to generate accurate, timely, and actionable insights that support effective decision-making. Finally, the sixth step facilitates interaction with the digital models by end users, including policymakers, government agencies, and residents, via various interfaces such as web portals, mobile applications, and virtual reality platforms. This interaction supports critical activities such as policy formulation, disaster recovery, damage assessment, and evacuation planning.

Zhang, Wang and Wang (2019) presented a DT-based system for monitoring and predicting geological disasters, particularly in mountainous region. The system utilises Internet of Things (IoT), data-driven technologies, and neural network algorithms (machine learning models that mimic the complex functions of the human brain) for dynamic disaster prediction. With the increase in frequency and severity of geological disasters, the authors propose a novel approach towards a dynamic and intelligent early warning DT system. The system integrates physical and information space data, and utilises a BP (back propagation) neural network for dynamic prediction. The framework consists of a physical layer, an information layer, and a visualisation layer. The physical layer refers to the real-world geological environment, encompassing entities such as mountains and geological structures. The data is captured using IoT sensors, 3S technologies (remote sensing, GIS, and GPS), and automatic monitoring devices. The information layer is a digital replica of the physical layer and is responsible for real-time monitoring, prediction, and identification of early warning. The visualisation layer is designed for displaying data, models, and outcomes from the information layer, providing a visual representation of the geological environment and disaster information. The physical and informational layers constantly exchange data, providing a comprehensive prediction and early warning system for geological disasters.

Khan *et al.* (2022) discussed the role of DT technology in addressing challenges in Smart Cities, with a particular focus on protecting smart buildings during disasters, thereby ensuring resilience and safety. Similarly, Yuan *et al.* (2024) presented a framework for enhancing coastal risk recognition using Unmanned Aerial Vehicles (UAVs) and a DT framework to accurately monitor and assess the risks associated with a rapidly evolving tidal flat, thereby leading to more resilient and sustainable coastal management.

Henriksen *et al.* (2022) presented a national DT called the Hydrological Information and Prediction (HIP-DT) system, which provides detailed information on the hydrological cycle to support climate change adaptation, disaster risk reduction, and water management in Denmark. In a similar vein, Suquet *et al.* (2024) proposed a FloodDAM-digital twin prototype, designed to provide automated detection, mapping, prediction, and risk assessment of floods on both local and global scales.

A risk-informed DT concept integrating data-driven uncertainty quantification and risk analysis was developed by Alibrandi (2022) to support the sustainable and resilient design and management of smart buildings and infrastructure. In the broader Smart City domain, Ariyachandra and Wedawatta (2023) investigated the role of Digital Twin Smart Cities (DTSCs) in disaster risk management. Their study highlighted the potential of DTSCs to enhance disaster prevention, mitigation, and recovery efforts, while also addressing the inherent complexities and challenges faced by current disaster risk management systems. They proposed DTSCs as a comprehensive solution for improving the resilience and responsiveness of urban environments.

DTSCs synergise the capabilities of Digital Twins and Smart Cities by leveraging data collected from various Smart City components to develop digital replicas of urban systems. These digital twins enable a proactive approach to disaster risk management through the integration of advanced technologies, including UAVs, mobile crowd-sensing, IoT devices, AI, geo-tagging, and Big Data analytics.

1. **Unmanned Aerial Vehicles** (UAVs): UAVs are deployed in hazardous or inaccessible areas where traditional emergency vehicles cannot venture. They assist in locating victims, identifying alternate routes, and supporting communication infrastructure. UAVs can also enhance Smart City governance by keeping residents informed during disasters.
2. **Mobile Crowd-Sensing**: This technology enables the general public to contribute real-time data through their mobile devices. Information such as GPS coordinates, images, and social media content is uploaded to the cloud, facilitating data mining and intelligence gathering for disaster assessment and response.
3. **Internet of Things** (IoT): IoT sensors and devices provide real-time status updates during catastrophic events, enabling dynamic monitoring and response. IoT has proven valuable for disaster surveillance and early warning systems for geohazards such as floods, earthquakes, and landslides.
4. **Artificial Intelligence** (AI): AI models, trained on historical data, can predict socio-natural disasters. AI enhances the ability to forecast events like floods, forest fires, and volcanic eruptions, thereby saving lives and reducing economic losses. With more data, the accuracy of AI predictions further improves, allowing it to provide better forecasts than conventional methods.
5. **Geo-Tagging**: This technique estimates the geographic location of social media posts during disasters based on content and network metadata. It addresses the limitation of low rates of explicitly tagged posts, improving situational awareness.
6. **Big Data Analytics**: Big Data is fundamental to managing the vast volumes of information generated in Smart Cities. When integrated with the aforementioned technologies, it plays a crucial role in enabling accurate, timely, and effective disaster risk management and resilient Smart Cities.

Digital Twins hold transformative potential in emergency, crisis, disaster, and risk management by facilitating risk mitigation, strategic preparedness, rapid response, and efficient recovery (Cheng, Hou and Xu, 2023).

2.5 Technical Specification

An effective DT for risk and emergency management relies on a robust technical foundation consisting of various data sources, modelling techniques, and suitable software infrastructure.

2.6 Architecture and Components

A DT for risk and emergency management typically consists of several interconnected components. At its core is a detailed model of the physical asset, which could be a building, a network of infrastructure, or even a city. The model is often integrated from a Building Information Model (BIM) or a reality mesh. A unique feature of DTs is the continuous streaming of real-time data from the field through: IoT sensors (monitoring structural health and environmental conditions, etc.), remote sensing satellites, drones, traffic cameras, weather stations, social media feeds, and other dynamic data sources (Ariyachandra and Wedawatta, 2023). The data pipeline is central to the DT architecture, and it streams multivariate, heterogeneous data into the twin's database. For instance, an urban disaster management DT might receive live inputs from accelerometers on bridges, LiDAR scans from UAVs, and even crowdsourced information from citizens' social media feeds (Ariyachandra and Wedawatta, 2023). Such multi-modal sensing is crucial to ensure the twin reflects the ground reality in an evolving emergency scenario.

2.7 Data Integration and Analysis

Once acquired, the raw data is processed and integrated into the DT. This involves data fusion techniques or databases to store the information, and an analytics module to extract useful insights. A variety of modelling techniques are employed: physics-based simulation (for example, finite-element models to simulate structural response to natural disasters), AI and machine learning (ML) models for pattern recognition and prediction, and graph or network models to capture interdependencies in infrastructure or social networks (Cheng, Hou and Xu, 2023). For emergency management, ML can be integrated with DTs for tasks like anomaly detection (identifying signs of failure in sensors), predictive analytics (for example, forecasting the outbreak or spread of wildfires), and natural language processing (to analyse crisis communication). All these models can run using on-premise servers or cloud computing infrastructure. Cloud computing is often preferred for handling intensive computations and large data volumes (Wolf *et al.*, 2022). Cost-effective, on-demand cloud infrastructure, such as Microsoft Azure or AWS, allow for the processing of big data streams at high resolution, which is essential for real-time emergency management.

2.8 Platform

The deployment of DTs for emergency management relies on a diverse set of software platforms and underlying infrastructure. A range of platforms, both commercial and open-source, are available for building and managing DTs. Some of these include Ansys Twin Builder, GE Digital Twin software, Altair SmartWorks, Bentley iTwin, and Siemens Digital Twin.

Ensuring interoperability with existing systems is crucial for ensuring smooth integration and operation. This includes integration with Geographic Information Systems (GIS) for spatial data integration and mapping, and BIM systems that provide detailed information about the design of buildings and infrastructure. The adoption of open APIs is vital for smooth data exchange and integration between different components of the DT ecosystem and with external systems. The choice of software platform and supporting infrastructure should be guided by the specific functional and technical requirements of the intended DT application.

2.9 Simulation and Visualisation

A range of sophisticated modelling techniques are employed within DTs to simulate emergencies, predict their impact, and evaluate potential response strategies. The DT serves as a sandbox environment to run what-if scenarios for a range of emergencies. Simulation methodologies, ranging from models that simulate the behaviour of individuals during an emergency to scenario-based simulations that explore different potential disaster trajectories and the effectiveness of various interventions under different conditions, are a fundamental aspect of DTs for emergency management.

In terms of visualisation, DT platforms often include dashboard interfaces and sometimes 3D immersive experiences for users. This allows for visualising the evolving state of an emergency over a 3D map of a city embedded with sensor readings and predictive indicators. Such interfaces facilitate the understanding of complex data. They are often referred to as Digital Twin Smart City (DTSC), involving intelligent dashboards that monitor emerging threats and suggest potential steps to mitigate their impact (Ariyachandra and Wedawatta, 2023). The technical ecosystem of a DT for emergency management largely depends on factors such as the scale of the system being modelled, the complexity of required simulations, the volume of real-time data processing, and the desired level of integration with preexisting systems.

At its core, DTs utilises technologies such as AI, Big Data, Cloud Computing, IoT, and virtual and augmented reality (VR and AR). Some of the underlying technologies used by DTs for risk, emergency, disaster, and crisis management are:

1) Integration of multiple sources of data

2) Computer vision

3) Sensors and IoT

4) Extended reality

Yu and He (2022) propose a framework for a digital twin-driven intelligent disaster prevention and mitigation for infrastructure. Their framework is built on five layers:

1) **Data layer**: This layer includes design and construction data (e.g. BIM models, CAD drawings, simulations) and maintenance and catastrophe data (e.g. sensor readings, UAV footage, laser scans, satellite imagery). This layer provides the information necessary to assess disaster prevention and mitigation capabilities, facilitating informed decision-making.

2) **Object layer**: The object layer consists of physical and virtual objects. Physical objects include the actual infrastructure itself, along with the necessary equipment and relevant environmental information. Virtual objects include digital representations of their physical counterparts. The virtual objects are created and updated periodically using reverse modelling technology, enabling accurate disaster reproduction.

3) **Technology layer**: The technology layer comprises the technologies and algorithms that power the digital twin-driven intelligent disaster prevention and mitigation for infrastructure (DT-IDPMI) system. It includes:

- Information fusion technology: With a multitude of different data sources, information fusion technology plays an integral role in merging and analysing the data to aid in decision-making.
- Data analysis and generation algorithms: The DT-IDPMI system would rely on sophisticated algorithms capable of handling big datasets and providing real-time predictions. They require careful selection, taking into account their accuracy, efficiency, and applicability to the DT context.
- Reverse modelling technology: This technology is used to create and update virtual models based on real-world data. Frequently used reverse modelling approaches include the BIM-based modelling, Agisoft Metashape, and the physical path method.
- Interactive optimisation for design: A key advantage of a DT system is its capacity to support interactive optimisation across all stages of the design process, particularly in response to structural defects, system failures, and disaster scenarios. The integration of a DT with Integrated Design Process for Multi-Hazard Infrastructure (DT-IDPMI) enables iterative design enhancements under diverse disaster conditions, ultimately leading to the development of more resilient and adaptive infrastructure systems.
- Extended reality (ER): ER technologies like VR and AR bolster the DT-IDPMI system by creating interactive and immersive experiences for participants. This greatly benefits the customer experience, helps designers detect potential flaws, and assists constructors in planning and developing effective disaster management strategies.

4) **Connection layer:** The connection layer ensures seamless and reliable data transmission between the physical and virtual components of the DT-IDPMI system. Some frequently used connection layer technologies include Bluetooth, WiFi, NFC, UWB, satellite, and shortwave communication. Due to the real-time data requirements and harsh environments during disasters, communication technologies at this layer must be fast, compatible, stable, and robust. In line with these requirements, 5G stands out as one of the most promising solutions.

5) **Service layer:** The service layer's purpose is to translate the analysis and insights from the DT-IDPMI system into actionable services tailored to specific needs. In the design phase, the service layer would prioritise providing support for visualisation, optimisation, disaster preview, and ER. In the maintenance stage, the services would shift to include monitoring, diagnosis, fault prediction, visualisation, and life prediction. During disaster situations, the service layer plays a crucial role in providing real-time visualisation, damage assessment, casualty prediction and location, risk prediction, escape route planning, and supporting recovery efforts.

2.10 Benefits of Digital Twins

Emergency management framework consists of four main stages: mitigation, preparation, response, and recovery (Cheng, Hou and Xu, 2023). DTs can be extensively used in all four phases of emergency management.

Some of the benefits of using DTs to enhance emergency management include:

- **Data Integration and Analysis** - DTs can integrate multiple data sources, including sensor data, GIS information, social media data, remote sensing imagery, and crowdsourced data, to provide a comprehensive and real-time assessment of the situation during emergencies. This data integration, powered by AI and simulation technologies, enables efficient data visualisation and analysis, which is essential for making well-informed decisions (Cheng, Hou and Xu, 2023).
- **Data Collaboration and Information Sharing** - Disasters typically involve many actors: government agencies, emergency responders, utility companies, NGOs, and the public. DTs facilitate seamless information exchange between different organisations, enabling real-time collaboration between various stakeholders involved in emergency management (Cheng, Hou and Xu, 2023; Fan *et al.*, 2019). A DT can act as a shared canvas for these stakeholders. By having a unified model that all parties can access, communication is improved, and decisions can be based on the same data and simulations. This is especially crucial during large-scale disasters where a coordinated response is required. For example, during a city-wide incident, the fire service and

police can jointly use a DT of the city to coordinate, for example, the rerouting of traffic away from the incident site.

- **Resource Allocation and Response** - During the response phase, DTs enable efficient resource allocation and scheduling by providing real-time information on the affected areas and severity of the emergency (Cheng, Hou and Xu, 2023; Fan *et al.*, 2019). This ensures limited resources such as medical supplies, rescue workers, and shelter facilities are deployed rapidly and efficiently to areas where they are most required.
- **Damage Assessment and Recovery** - During the recovery phase, DTs can assist in damage assessment by analysing data from various sources such as remote sensing imagery and social media. This information helps identify the location and the full extent of the damage, assess losses, and prioritise recovery efforts (Cheng, Hou and Xu, 2023). DTs also facilitate information exchange and collaboration between various stakeholders, allowing an organised and efficient recovery process.
- **Training and Preparedness** - DTs are not only valuable during an ongoing emergency, but also before disasters strike. A major benefit is the ability to use DTs as a tool for training and scenario planning. Emergency drills and training can be conducted in the virtual environment, mimicking realistic disaster conditions, allowing emergency responders to practice and experience handling different emergency scenarios. For instance, a city can run a simulated earthquake through DT, and run staff training on evacuation protocols, search-and-rescue, and inter-agency coordination. Such virtual training can be more immersive than tabletop exercises (Cheng, Hou and Xu, 2023).
- **Improved Resilience** - In the long term, the use of DTs contributes to greater disaster resilience and faster recovery. By continuously monitoring infrastructure and systems, DTs can identify vulnerabilities and anomalies before they pose a threat, enabling preventive repair and maintenance. For example, a DT of a bridge might detect abnormal vibrations indicating structural issues, prompting immediate repair and preventing collapse (Ariyachandra and Wedawatta, 2023). When a disaster strikes, DTs can expedite damage assessment and recovery. The DT can be updated with post-disaster data (using drone photogrammetry and sensor data) to provide an extent of damage and assist in rebuilding strategies.

- **Risk Assessment and Early Warnings** - DTs can continuously monitor potential disaster-prone sites (sites of interest) for anomalies and risks by analysing real-time sensor data and historical disaster data. By spotting patterns and predicting potential disasters, early warnings can be issued to the authorities and the public, allowing proactive risk mitigation and prompt preparation efforts (Cheng, Hou and Xu, 2023).

Overall, DTs serve as a transformative tool for emergency management, with the ability to shift from reactive to proactive methods, allowing early risk identification and mitigation, enhancing cooperation and collaboration between various stakeholders involved in emergency response, and boosting the efficiency and effectiveness of disaster preparedness, response, and recovery.

2.11 Challenges

While the potential of Digital Twins (DTs) in emergency management is substantial, several challenges and limitations must be addressed:

- **Data-related Challenges:** Within the context of Emergency Management of Civil and Infrastructure (EMCI), Cheng, Hou and Xu (2023) highlight issues related to data quality and access. Effective DT implementation relies on large volumes of accurate data from diverse sources, such as remote sensing, social media, and crowdsourced inputs. However, these sources often contain noise, inaccuracies, and bias, which can undermine the reliability of the system.

- **Data Reliability and Verification:** Fan *et al.* (2019) similarly emphasise the limitation of DTs due to their dependence on heterogeneous data sources. The presence of false or misleading information poses serious risks to the reliability and accuracy of emergency management systems. To mitigate this, Cheng, Hou and Xu (2023) advocate for the use of technologies such as AI and ML to filter, verify, and exclude unreliable data.

- **Restricted Data Access:** Another concern raised by Cheng, Hou and Xu (2023) is the difficulty in accessing certain types of data due to their sensitive nature or national security restrictions, which can limit the completeness and functionality of DT systems.

- **Ethical and Privacy Concerns:** Cheng, Hou and Xu (2023) also underscore ethical issues and privacy risks associated with data use in DTs for emergency management. Since DTs process vast amounts of sensitive data, including personal, geolocation, surveillance, and social media information, there are significant concerns around how this data is collected, stored, and utilised. These risks are further magnified in city-wide DT implementations. Additionally, concerns around equity and fair access have been raised. As noted by Ariyachandra and Wedawatta (2023), there is a risk that technologically advanced, affluent communities may benefit disproportionately from DTs, while marginalised populations could be excluded or underserved.
- **AI Explainability:** The reliance on AI in DT systems for disaster analysis and forecasting introduces another challenge: the lack of transparency in AI decision-making processes. Cheng, Hou and Xu (2023) note the importance of model interpretability to build trust and ensure broader acceptance of AI-based predictions. Future DT systems should prioritise explainable AI to address this issue.
- **Model Accuracy and Reliability:** The effectiveness of DTs in emergency scenarios hinges on the accuracy and reliability of their simulations. However, replicating complex real-world systems with high fidelity remains a significant challenge (Riaz, McAfee, and Gharbia, 2023). The performance of AI and ML algorithms within DTs is highly dependent on the quality and completeness of training data; biased or incomplete data can result in flawed predictions and poor decision-making during crises (Brucherseifer *et al.*, 2025).
- **High Costs:** The financial burden of implementing DT technology is another limiting factor. As Mchirgui *et al.* (2024) point out, initial investments, including sophisticated modelling, sensor deployment, and AI/ML integration, can be substantial. Ongoing operational costs, including data processing, storage, and cybersecurity, further add to the expense. These financial challenges may deter adoption, especially among public sector organisations and small firms.
- **Infrastructure and Data Management Requirements:** DT systems, particularly Digital Twin Smart Cities, require robust data infrastructure, efficient data management systems, and advanced analytics capabilities to operate effectively (Mchirgui *et al.*,

2024). Without these foundational elements, the performance and scalability of DTs in emergency contexts may be compromised.

- **Balancing Accuracy and Computational Efficiency:** Achieving real-time responsiveness during emergencies necessitates a careful trade-off between model accuracy and computational efficiency. Chang *et al.* (2024) emphasise the need for ongoing research to optimise this balance to ensure that DT systems can perform effectively under time-sensitive conditions.

2.12 The Future

Digital Twin (DT) technology is poised to transform the future of emergency and risk management, offering unprecedented capabilities for preparedness, response, recovery, and informed decision-making across a wide range of emergency scenarios.

- **Cybersecurity and Trustworthiness:** A key concern in deploying DTs for emergency management is ensuring their security and resilience against cyberattacks. Cheng, Hou and Xu (2023) emphasise the importance of developing secure and trustworthy DT systems, suggesting that future research should explore the integration of advanced technologies, such as deep learning, neural networks, and blockchain. While traditional cybersecurity measures, such as firewalls and intrusion detection systems, have been employed, the increasing sophistication of cyber threats necessitates more robust and adaptive solutions. Similarly, Zio and Miqueles (2024) point to cybersecurity and reliability challenges in the application of DTs for safety and risk assessment.
- **Urban Emergency Management and Flooding:** DTs are expected to play a critical role in urban emergency management, particularly for flood events. Ge and Qin (2024) propose a generative city DT system designed to offer real-time visual situational awareness, XR-based interaction, and decision support during flooding caused by heavy rainfall. This system supports real-time collaboration and coordination among stakeholders, a key requirement for effective flood response.

- **Smart Cities and Future Applications:** As urban environments grow in complexity and exposure to risks, the integration of Digital Twin and Smart City (DTSC) technologies is becoming central to enhancing urban resilience. DTSCs combine Smart City infrastructure with DT capabilities to create a dynamic digital replica of the urban landscape. Leveraging real-time data from IoT devices and sensor networks, DTSCs enable continuous monitoring and predictive analysis of potential disaster scenarios, allowing for proactive risk mitigation (Ariyachandra and Wedawatta, 2023).
- **Infrastructure Monitoring and Maintenance:** In future applications, DTs will enable continuous monitoring and predictive maintenance of critical infrastructure, reducing the likelihood of system failures during emergencies. Advanced simulations, combined with real-time data integration, will improve the operational resilience of complex systems such as power grids (Mchirgui *et al.*, 2024). DTs will also enhance inter-agency communication and resource coordination, addressing longstanding gaps in emergency management (Ahmed and Currie, 2024).
- **AI Integration and System Cohesion:** The integration of AI with DTs will significantly enhance predictive accuracy and automate various aspects of emergency preparedness, response, and recovery. Future developments will focus on creating more cohesive DT frameworks across sectors, improving system interoperability. As these systems become more widespread, attention must also be given to privacy protection and ethical data use (Mchirgui *et al.*, 2024).
- **Research Directions:** Future research should prioritise the development of dynamic, adaptive models capable of incorporating diverse data sources. There is also a growing need to understand the social dynamics and interdependencies of urban systems to maximise the utility of DTs in disaster scenarios (Lagap and Ghaffarian, 2024).
- **Outlook:** The future of DT technology in emergency and risk management is promising. With continued advancements in hardware, software, and systems integration, DTs are set to become essential tools for enhancing resilience and protecting infrastructure from an expanding range of risks.

3.0 Case Study: Dublin Fire Brigade

3.1 Overview

Dublin Fire Brigade (DFB) is a multifaceted organisation responsible for firefighting, emergency medical services (EMS), and emergency management for the Dublin city and county region, serving a population of over 1.4 million (DFB Annual Report, 2023). Established in 1862, DFB has a long history of serving the community and plays a crucial role in ensuring public safety across Dublin. It operates a fleet of 143 vehicles, which includes fire appliances, ambulances, and specialised units. In 2023, DFB handled 207,575 emergency calls, responded to 80,916 EMS mobilisations, and 34,927 fire and rescue mobilisations (DFB Annual Report, 2023).

As part of its Emergency Medical Services (EMS), all DFB firefighters are trained as paramedics and capable of providing advanced paramedic and paramedic-level care. DFB operates 14 emergency ambulances staffed by paramedics and is on call around the clock, 365 days a year (DFB Annual Report, 2023). Apart from firefighting and EMS, DFB also promotes fire prevention and community fire safety through fire safety campaigns, inspections, and outreach programmes.

DFB collaborates with various agencies to respond to major emergencies, including An Garda Síochána (the Irish Police Service), the Health Service Executive, the National Ambulance Service, the Irish Defence Forces, and the Irish Coast Guard (DFB Annual Report, 2023). DFB is an integral part of Dublin's emergency services, providing a comprehensive response that combines firefighting, rescue, and medical services. With its dual operating model, highly skilled workforce, and strong commitment to public safety, DFB is internationally recognised as a model of good practice in emergency service delivery.

The concept of the DT within DFB originated from its drone programme, which focused on 3D data capture using photogrammetry rather than traditional 2D mapping (DFBSO). This initiative was established to create detailed 3D models of complex or high-risk sites, such as St. Patrick's Cathedral, highlighting key features, including access points, emergency routes, and potential hazards. This development marked a significant shift from static maps to interactive, intuitive models designed to enhance situational awareness and support pre-incident planning for firefighters (DFBSO).

The genesis of DFB's Digital Twin for Emergency Response (DTER) initiative aligned with the broader Smart City strategy led by Dublin City Council (DCC). This city-wide initiative created a valuable opportunity to explore innovation in emergency and risk management. Moreover, the strategic collaboration between DFB, Bentley Systems, and DCC fostered a strategic, synergistic partnership that laid the groundwork for research and development of the DTER initiative (DFBSO).

3.2 Technical Specification

DFB uses the following platforms, software, and tools to build and operate its Digital Twin for Emergency Response (DTER) programme:

Platforms

1. **Bentley OpenCities Planner:** This is DFB's primary platform for DT technology, serving as the visual interface ("front end") for 3D maps and associated data (DFBSO). Users can toggle features and layers on or off according to their operational needs. The DT is accessible via a web browser, requiring no additional software or configurations (DFBSO). The platform enables seamless collaboration among Dublin City Council (DCC), Dublin Fire Brigade (DFB), and the academic partner Dublin City University (DCU), who can all access and work on shared models (DFBSO).
2. **Esri ArcGIS Online:** This cloud-based Geographic Information System (GIS) platform is used by DFB to manage and store geospatial data such as building polygons, fire hydrants, and fire safety notices (DFBSO). ArcGIS acts as a centralised geospatial data repository, and the stored data can be accessed and visualised within the DT environment (DFBSO).
3. **Bentley iTwin Platform (formerly ContextCapture):** This software processes large volumes of high-resolution drone imagery to construct 3D reality meshes of various locations, including St. Patrick's Cathedral (DFBSO). The generated 3D models are then uploaded to OpenCities Planner and integrated into the Digital Twin (DFBSO).

Tools

- **Drones:** DFB utilises drones to capture high-resolution site imagery to generate 3D reality meshes. These images are processed through Bentley's iTwin platform to create detailed 3D models, which are subsequently uploaded into OpenCities Planner for integration into the DT system (DFBSO).

Data

- **Building Information Models (BIM):** BIM data plays a significant role in DTER. BIM models for specific sites are integrated into the DT via OpenCities Planner (DFBSO). In some cases, building owners provide detailed internal data, including fire systems, hydrants, and alarm panels, which enhances situational awareness. BIM data can also be used to automate calculations, such as measuring distances to fire exits or evaluating access point lengths (DFBSO).
- **Real-Time Data Streams:** DFB has ambitious plans to incorporate real-time data into its DT framework. Potential data sources include GPS telemetry, environmental sensors, inventory systems, and fire alarm panels (DFBSO). Successful integration depends on factors such as data governance, financial cost, and technical feasibility.
- **Database Integration:** A cloud-based database, such as PostgreSQL hosted on Amazon Web Services (AWS), is used to store and merge various datasets, including spatial data, demographic data, and information from the Residential Tenancy Board, GeoDirectory, and Valuation Office (DFBSO). This data can be visualised and integrated directly into OpenCities Planner to enrich the Digital Twin environment.

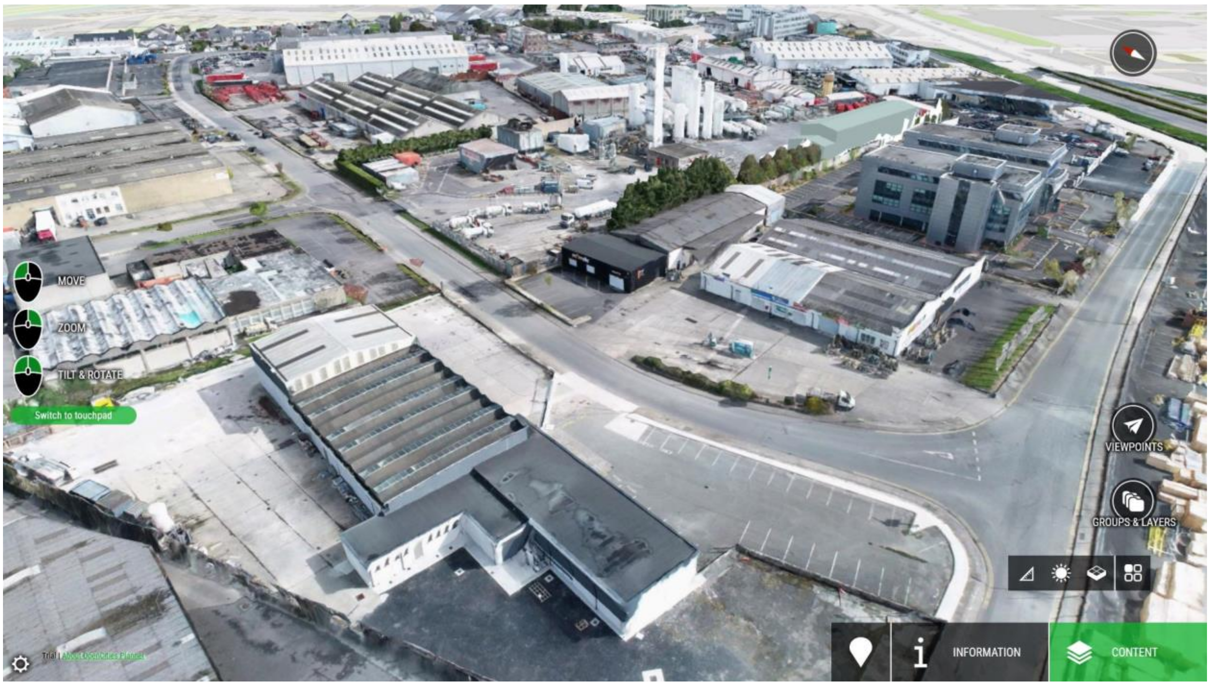

Figure 5: DFB's DTER Digital Twin Platform Captures a High-Risk Site

Figure 6: DTER Platform Showcasing Risk Visualisation Features

3.3 Benefits

Benefits of Digital Twins for Emergency Response (DTER) for Dublin Fire Brigade (DFB) include:

1. **Increased Operational Efficiency:** One of the most significant benefits of implementing DTs is improved operational efficiency, particularly in managing and reusing data (DFBSO). DTs consolidate information from multiple sources into a single platform, enabling more effective data management and analysis. For example, data from drone imagery, BIM models, and other sources can be captured once and reused repeatedly, as such data tends to remain stable over time. Any subsequent changes to site data can be flagged and updated accordingly (DFBSO). DTs also allow for the automation of manual tasks, such as measuring building entrances and exits or calculating travel times to emergency exits (DFBSO). With BIM integration, "automated geometry" can be extracted, reducing the workload of fire engineers and allowing them to focus on complex design and safety issues, thereby enhancing overall efficiency (DFBSO).

2. **Improved Pre-Incident Planning:** DTs offer interactive, detailed 3D models of sites that include key elements such as access points, potential hazards, and other points of interest (DFBSO). This enables firefighters to familiarise themselves with locations prior to an incident, improving situational understanding and supporting the development of more effective incident management plans (DFBSO).

3. **Enhanced Training Capabilities:** DTs can be leveraged as immersive training tools, allowing realistic simulation of emergency scenarios for better preparedness and incident response (DFBSO). This enhances the training experience, increases engagement, and improves readiness for real-world situations.

4. **Better Decision-Making:** By providing comprehensive, accurate, and potentially real-time information, DTs support improved decision-making for incident commanders during both emergency planning and response (DFBSO). This helps reduce cognitive overload, minimises risk to firefighters, and allows for faster incident resolution and prioritisation of resources (DFBSO).

5. **Improved Interoperability:** DTs can integrate real-time data from various sources, such as sensors, GPS systems, and incident logs, creating a unified "common operating

picture" for all emergency responders (DFBSO). This shared operational view enhances situational awareness and facilitates coordinated action between services, such as fire and ambulance teams, during emergencies.

6. **Climate Risk Modelling:** DTs offer capabilities for modelling and simulating climate-related risks, such as flooding and extreme weather events (DFBSO). These simulations can inform mitigation strategies and enhance the preparedness and resilience of Smart Cities against the impacts of climate change.

7. **Enhanced Communication and Collaboration:** DTs enable more effective communication and collaboration across DFB departments and with external agencies, such as the National Ambulance Service (DFBSO). By providing a shared platform for accessing and exchanging data, DTs help break down organisational silos and promote an integrated approach to emergency management.

3.4 Challenges

Some of the challenges associated with the Digital Twins for Emergency Response programme (DTER) in DFB include:

1. **Difficulty with BIM Integration:** Integrating Building Information Models (BIM) into DT systems can be complex due to the high level of detail BIM files typically contain. To make them suitable for real-time applications within 3D models, much of this detail must first be simplified or removed (DFBSO). In addition, acquiring BIM data from building owners is often difficult, as "BIM models are very expensive to develop," and many existing buildings do not have such models readily available.

2. **Data Management:** Once relevant data has been collected, it must be efficiently integrated into the DTER platform (DFBSO). This involves retrieving information from data management systems, incorporating it into a functional DT, and presenting it in a user-friendly format that is actionable on the ground. This process is technically demanding and resource intensive. Furthermore, integrating large volumes of risk data on buildings across Dublin presents significant logistical challenges (DFBSO). The

ultimate objective is to include "every building within Dublin," with a particular focus "on the high-risk buildings."

3. **Data Maintenance:** Keeping the DTER platform current and accurate is another major challenge. Drone photogrammetry provides a snapshot of a site at a specific point in time, which means updates must be conducted regularly to reflect new developments or changes. This is typically undertaken on a "piecemeal basis" (DFBSO). A key concern is balancing the frequency and effort of updates with the level of risk posed by each site, especially when changes are small or infrequent.

4. **Technology Adoption:** As DTs are relatively new in the context of emergency response, there has been some scepticism and resistance to their adoption within DFB. Some fire officers perceive the technology as "cumbersome and laborious" (DFBSO). A phased rollout, supported by targeted training programmes, will be essential to build familiarity and acceptance among operational staff.

5. **Organisational Challenges:** As a "traditional organisation," DFB faces inherent challenges in integrating advanced technologies like DTs into its established workflows and operational culture (DFBSO). Existing processes are well-ingrained and often resource-constrained. Successfully adopting DTs will require a cultural shift and a willingness to embrace innovation across all levels of the organisation.

6. **Data Governance, Security, and Privacy:** DT systems rely heavily on the continuous flow of detailed and sometimes sensitive information, raising concerns about data governance, security, and privacy. Sharing data such as GPS telemetry, building sensor outputs, or inventory levels can be sensitive and risk-laden. For example, accessing a gas company's real-time fuel levels would require a "very tight agreement and a high degree of confidence" (DFBSO). Establishing robust governance frameworks and formal agreements with third-party stakeholders will be crucial to mitigating this risk.

7. **High Cost and Legislative Challenges:** Capturing high-resolution 3D models via drone surveys is costly. For instance, surveying just two square kilometres of Dublin's Docklands could cost "in the region of €20,000 to €30,000" (DFBSO), raising questions about cost-effectiveness in relation to use case. In addition, evolving drone regulations have introduced further complexities. "The legislation has changed a lot in the last few

years in terms of drone capture," making it more difficult to conduct surveys without securing multiple permissions from the aviation authority (DFBSO). Overcoming both the financial and regulatory barriers will be essential for scaling the DTER programme in DFB.

3.5 The Future

There is immense future potential for DTs for emergency and risk management in DFB and beyond. A key focus for the next three years is expanding from the current 2D mapping to 3D mapping, including DTs, particularly in managing complex incidents and major emergencies (DFBSO). Initially, 2D mapping will be fully implemented for smaller, routine incidents like "domestic fires and traffic accidents", while 3D will be introduced to improve incident information management, especially for large-scale incidents and emergencies (DFBSO).

The 3D technology is still in the prototype stage and is expected to be completed within the three-year timeline (DFBSO). An essential factor in the success of DTER is user-friendly design, ensuring simplicity on the front-end for the users, despite complex data being processed in the background (DFBSO). Future iterations could include simulation functionality for incident review and learning, and possibly seamless integration with other agencies like An Garda Síochána or the National Ambulance Service (including during multi-agency exercises) (DFBSO).

Scaling DTER across different regions and services is being considered, with its success largely dependent on infrastructure, data access capabilities, and strong support from senior management. Additionally, technical expertise will be critical to ensure successful implementation (DFBSO). For a city-wide scaling, a combination of technologies and strategies would be required. This could include leveraging readily available 3D tiles for broad coverage, utilising high-resolution drone models for specific sites, and incorporating BIM data where available (DFBSO).

Additional applications of DTER for the future include:

Familiarisation and Training: DTs can be used as a tool for familiarising crews with complex sites and newly-built infrastructure without requiring them to visit the location physically

(DFBSO). DTs can also be used to create "realistic training scenarios for incident command and management", using high-resolution 3D models (DFBSO).

Incorporating Additional Information and Streaming Data: Plans are in place to integrate various data sources, including weather data, tide levels, GPS telemetry from vehicles, building information sensors, and real-time data for enhanced preparedness and prediction (DFBSO).

Strategic Planning: A city-wide DT model offers significant potential for strategic planning by enabling the visualisation of the impact of new developments on the urban landscape. It can also be used to simulate scenarios related to climate change and urban resilience, such as flooding events and other extreme weather risks (DFBSO).

Overall, the potential benefits of DTs and the DTER programme for DFB and the broader emergency response community are significant, making the ongoing research and development of DT technology a valuable investment.

Note: DFBSO refers to interviews completed with a key informant in the DTER programme - Dublin Fire Brigade Station Officer (Organisational Intelligence Unit)

4.0 Case Study: Smart DCU (Dublin City University)

4.1 Overview

The Smart DCU initiative is an ambitious project designed to develop and test cutting-edge technologies within the university campus environment, with the aim of scaling successful solutions to the city level (Smart DCU, 2024). The initiative focuses on harnessing innovative digital technologies, such as DTs, data analytics, and smart sensors, to optimise campus operations, enhance safety, and promote sustainability.

Smart DCU is part of the broader Smart Dublin programme, which seeks to transform Dublin into a smarter, more innovative, and sustainable city through the integration of emerging technologies (Smart DCU, 2024). Launched in 2019, the initiative is a collaborative effort involving Dublin City Council, the Insight SFI Research Centre for Data Analytics, and DCU Alpha. Notable ongoing projects under Smart DCU include the Digital Twin project and the Autism-Friendly University project.

The DCU Digital Twin project, a key component of Smart DCU, is led by Dr. Ali Intizar in partnership with Bentley Systems and the Insight Research Ireland Centre for Data Analytics. The project aims to create digital twin models of DCU's campuses by leveraging advanced technologies, including AI, data analytics, IoT, and computer vision.

The initial concept for the project emerged from Smart DCU's interest in developing a live, immersive experience that extended beyond traditional 2D mapping platforms, such as Google Maps (SDA). This exploration led to a collaboration with Bentley Systems, whose best-in-class software and tools enabled the creation of high-fidelity 3D models, marking the beginning of an innovative partnership and DCU's journey into DT technology (SDA).

A secondary objective of the project was to identify relevant use cases once the campus DT models were established (SDA). The strategy was to first build the immersive DT environment and then identify practical challenges that the technology could help address. Early applications included the Campus Explorer, a tool designed for prospective students and individuals with autism, as well as a tailored use case for the Dublin Fire Brigade (SDA).

4.2 Technical Specification

Smart DCU deploys the following Tools and Platforms:

1. **Bentley's OpenCities Planner:** A lightweight, cloud-based platform used for hosting and visualising DCU's DT models. It allows users to view 3D models of the campuses and customise various layers and features. The Campus Explorer application is built entirely on OpenCities Planner for its DT implementation (SDK, SDJ).

2. **Bentley's iTwin Platform and iTwin Capture Modeler:** The iTwin Platform is a cloud-based solution designed to support the creation and operation of DTs for infrastructure assets. It provides services for the integration, visualisation, and analysis of data from multiple sources, including reality data. At DCU, it is extensively used for storing and managing 3D models (SDJ).

   iTwin Capture Modeler (formerly ContextCapture) is a reality modelling tool that creates highly accurate 3D models of infrastructure from drone imagery and point clouds. It was used to process all collected imagery and generate reality meshes. The resulting 3D models offer significantly higher resolution compared to basic BIMs (SDJ).

3. **Unreal Engine:** A game engine platform used to merge reality meshes, BIMs, and streaming IoT sensor data, enabling the creation of a hyper-realistic digital twin (SDK). Unreal Engine supports immersive campus experiences, virtual environments, and game-style navigation, with advanced visualisations such as wind effects, avatars, and dynamic elements.

   Using Unreal Engine, the Smart DCU team developed an interactive avatar within the 3D model (SDK). The avatar can be user-controlled, allowing the DT to serve as an engaging tool for campus exploration, navigation, and emergency planning. However, Unreal Engine is resource-intensive and requires high-end GPUs and considerable bandwidth to function effectively (SDK, SDJ).

4. **Bentley's 4D Analytics:** A middleware platform that integrates data from diverse IoT sensors into a centralised analytics hub. It addresses the challenge of connecting sensors that use different APIs by acting as a unified data dashboard (SDK, SDJ).

End-to-End Digital Twin Creation Workflow

1. **Data Collection:** Data for 3D models was collected through a combination of drone photogrammetry (for outdoor areas), laser cameras, and iPhones (for indoor spaces). BIM models can also supplement this data at this stage.

   Drones: A DJI Mavic 2 Pro drone was used to capture aerial imagery of the DCU campuses. These images were processed using photogrammetry software and Bentley's OpenCities Planner to construct 3D models (SDK). The drone survey was conducted at an altitude of 100 metres, capturing approximately 1,749 images of the Glasnevin campus.

   iPhone 14 Pro: Used for scanning smaller indoor spaces such as the Interfaith Centre at DCU (SDK, SDJ). Applications like Polycam are employed for both capturing and processing the imagery.

   Laser Camera: Deployed for scanning larger or more complex interior spaces, such as the U Building, where iPhone capture is insufficient (SDK). The laser scanner generates a "point cloud", a dense set of data points that digitally represent the environment.

2. **Image Processing and 3D Model Creation**: The captured images are processed using Bentley's iTwin Capture Modeller to produce point clouds and 3D models of the physical space. Indoor images captured by iPhone are processed using Polycam.

3. **IoT Data Streaming**: A variety of IoT sensors across the campus continuously stream real-time data. These include bin-level sensors, sound sensors, environmental sensors (light, humidity, temperature, movement), and computer vision-based cameras (SDK, SDJ). Each sensor has its own API, and Bentley's 4D Analytics acts as the integrative dashboard to access and visualise this data.

4. **Data Integration and Visualisation:** Live IoT data streams are embedded into the 3D model, linking sensor outputs to specific spatial locations within the DT (SDJ). This integration forms an operational DT, allowing users to monitor real-time sensor data within the 3D environment. The result is continuous, data-driven analysis, insight generation, and decision-making for managing the physical site.

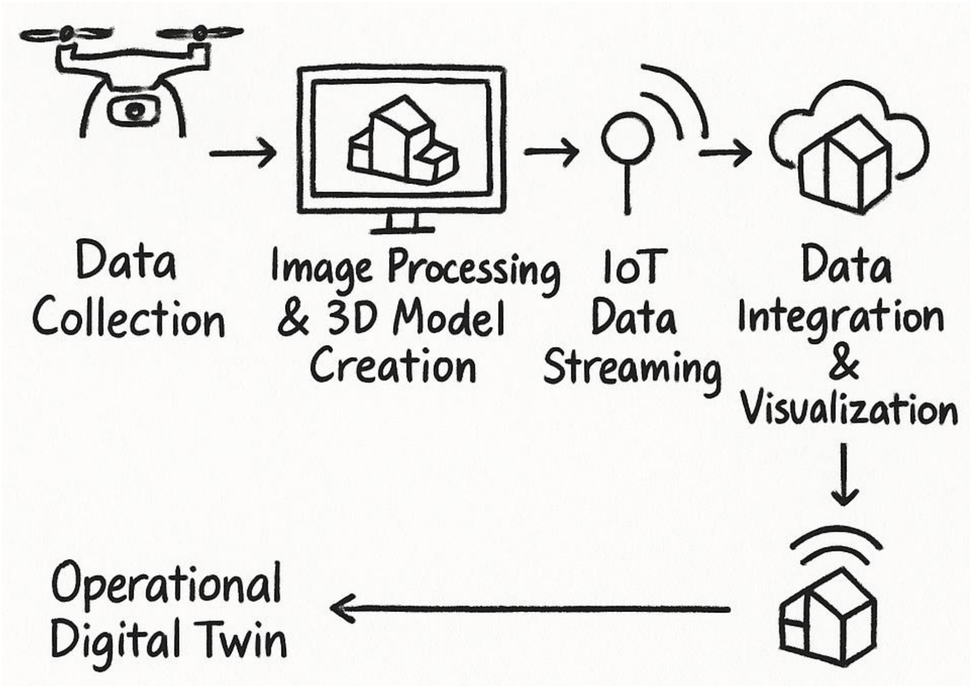

Figure 7: Simplified Digital Twin Creation Workflow

It is worth noting that, although the project primarily utilises Bentley Systems' software and standards for its DT, the project as a whole is platform-agnostic. This ensures the components can be swapped out for other technologies in the future (SDK).

Figure 8: DCU Glasnevin Campus Digital Twin (using OpenCities Planner)

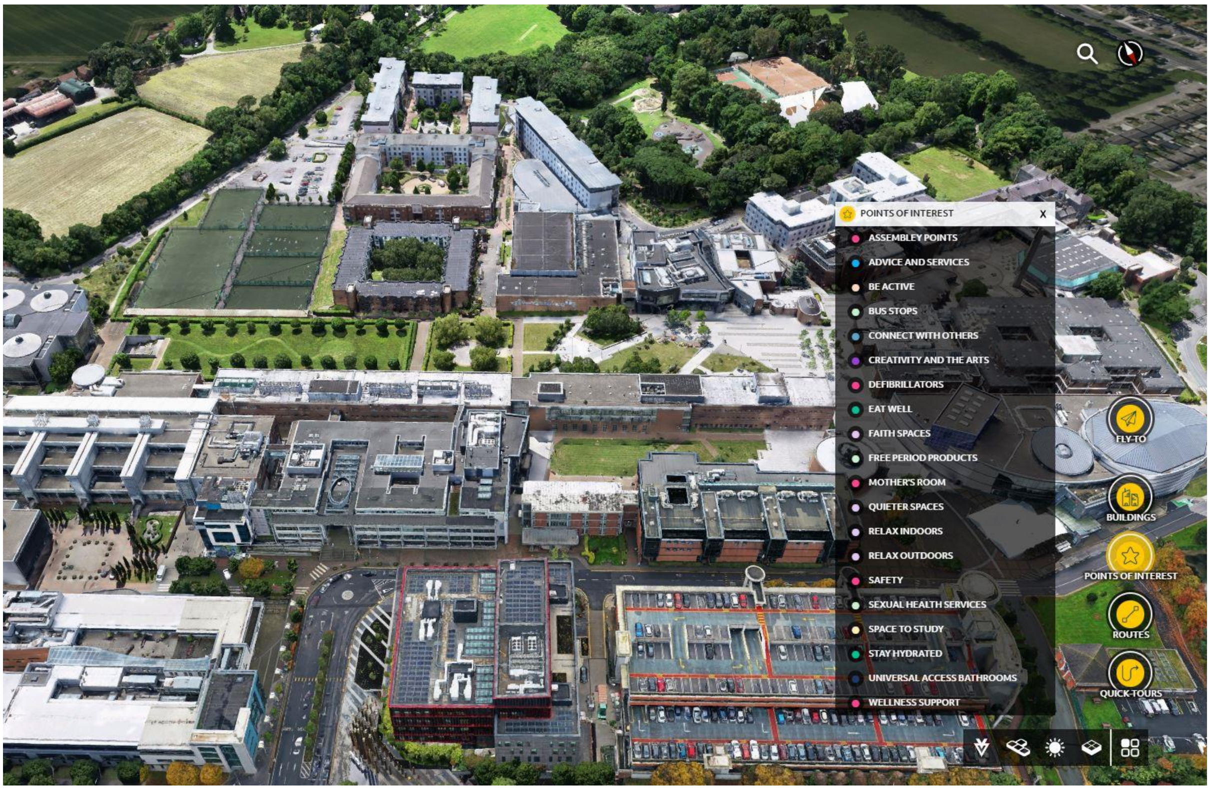

Figure 9: DCU Glasnevin Campus Digital Twin Displaying Various Features

Figure 10: Immersive Digital Twin in VR (using Unreal Engine)

4.3 Benefits

By combining data from 3D models with real-time information from IoT sensors, DTs unlock significant potential and offer numerous benefits. Some of the benefits of Smart DCU's DT technology include:

1) **Optimising Room Occupancy**: The current method for assessing the room occupancy of classrooms involves a manual process where an employee is sent into each room to record the number of people present (SDK). This labour-intensive approach can be automated and improved using DTs. By integrating computer vision and IoT sensors, classroom usage can be monitored in real-time. This leads to efficient resource utilisation and substantial cost savings. This approach also has the potential to solve the issue of phantom bookings, which refers to the practice of reserving multiple classrooms for a lecture or meeting but not using all of them (SDK).

2) **Enhancing Campus Operations and Maintenance**: Digital twin models can be leveraged for simulation and modelling, providing valuable insights into maintenance and repair needs. For example, aerial imagery captured by drones can be used to survey rooftops and detect potential leaks, with this information directly integrated into the DT model (SDK). Additionally, DTs can serve as a shared platform for cross-departmental communication and collaboration on campus-related issues (SDA, SDK). Compared to traditional methods, using DTs for maintenance planning and issue resolution is often faster, more efficient, and data-driven.

3) Real-Time Information and Navigation: DTs can be integrated with real-time data sources to provide users with live campus information. The DT system gathers data from a range of IoT sensors, including bin-level sensors, sound sensors, indoor environmental sensors, and air quality monitors (SDK). These sensors transmit data periodically via a low-power wide area network (LoRa) (SDK). A future goal is to incorporate additional real-time data streams, such as public transport schedules, room availability, and event information, directly into the DT model (SDK).

Applications like Campus Explorer can help students and staff navigate the campus more easily. For instance, users can input a room number and view step-by-step directions, including building entrances and the optimal path to their destination, displayed within the DT environment (SDK). This functionality is particularly beneficial for new students and individuals with additional needs, improving campus accessibility and user confidence.

4) Autism-Friendly University: DCU became the world's first Autism-Friendly University, a distinction achieved through a commitment to inclusive design across teaching, services, and the campus environment (Dublin City University, 2023). Building on this initiative, Smart DCU has introduced further measures to support students with Autism Spectrum Disorder (ASD) (Fernandez *et al.*, 2024). One key development is Campus Explorer, a browser-based DT designed to support autism-friendly navigation. Initially conceived to create calm, clear pathfinding solutions, this tool helps individuals with autism navigate DCU's buildings and spaces more comfortably (SDK).

5) Campus Safety and Security: With multiple DCU campuses mapped in detail, the DT model plays a crucial role in enhancing student safety and campus-wide security. DTs support pre-incident planning and emergency response, enabling more coordinated and informed action during emergencies (SDA, SDJ). This contributes to a safer and more resilient campus environment.

6) Scenario Planning for Emergency Response: DTs can simulate various emergency scenarios, such as flooding or other socio-natural disasters, and assess their potential impact on the campus (SDK). These simulations support the development of robust emergency response plans. For example, ongoing research is exploring the use of DTs to monitor flood-prone areas across the campus (SDK, SDJ), helping to inform both mitigation and response strategies.

7) Increased Transparency and Accountability: DTs promote greater transparency and accountability by offering a comprehensive, data-driven view of campus operations. This visibility supports evidence-based decision-making and progress tracking. For instance, DTs can be used to monitor energy consumption, identify inefficiencies, and highlight opportunities for sustainability improvements (SDA, SDK).

8) Improved Quality of Life: By providing real-time services, such as campus navigation, bus timetables, parking availability, and road congestion updates, DTs can significantly enhance the day-to-day experience of students and staff (SDA, SDJ). This integration of live information into a single, accessible platform supports convenience, efficiency, and overall quality of life on campus.

4.4 Challenges

Some of the challenges associated with implementing Smart DCU's DT are:

1. **Convincing Stakeholders:** One of the initial challenges was persuading various stakeholders within the university of the value of a DT. Many departments were either sceptical or preoccupied with daily operations, making them reluctant to engage with a new and unfamiliar technology (SDK). This resistance often stemmed from a limited understanding of the DT concept and its potential to enhance departmental functions (SDK, SDJ).
2. **Data Integration:** Creating a functional DT requires the integration of large volumes of heterogeneous data, such as drone imagery, laser scans, Polycam outputs, and IoT sensor feeds, each with different formats and APIs (SDA, SDK). Aligning and harmonising this data into a coherent and user-friendly model is a significant technical challenge that demands considerable expertise.
3. **Skillset Requirements:** Developing and maintaining a comprehensive 3D model demands a multidisciplinary team with skills in IT, graphics and multimedia, project management, and organisational strategy (SDK). Assembling such a team within a constrained budget was a significant hurdle in the early stages of the project.
4. **Computing Resource Requirements:** The software used for creating immersive DTs is computationally intensive and requires specialised hardware, including high-performance GPUs, to run effectively (SDA). Fully immersive environments also depend on VR headsets and controllers, which are rapidly evolving and can become outdated quickly.
5. **Data Security and Privacy:** Managing large datasets introduces inherent risks related to data privacy and security. The Smart DCU team addressed this by anonymising all data and excluding any personally identifiable information (SDK). In addition, strict data protection and management protocols were followed to ensure full compliance with data governance standards (SDJ).
6. **Scaling the Model:** The project began as a pilot, focusing on the creation and testing of a digital model of the DCU campus, with the long-term goal of scaling to a city-wide DT. However, this expansion presents major challenges, particularly in maintaining the

same level of detail and precision. Collecting and processing the immense volume of data required for a city-scale DT is technically complex and resource-intensive (SDK).

7. **Budget Constraints:** Financial limitations posed a considerable challenge, especially during the initial phases. A key issue was securing sponsorship for the aerial drone surveys, which were critical to building the DT model (SDK). Although several companies were willing to assist with technical expertise, the cost of data capture was a significant obstacle. This challenge was eventually overcome through a strategic partnership with Bentley Systems, which provided access to advanced software tools and expertise.
8. **Keeping the DT Up-to-Date:** Maintaining an accurate DT requires ongoing updates whenever physical changes occur on campus. This typically involves periodic drone surveys and data collection, which can be both time-consuming and costly (SDA, SDK). For instance, the recent construction of the Polaris building necessitated a fresh scan to reflect the updated campus layout (SDA).
9. **Limitations of Current Scanning Technologies:** While drone photogrammetry has proven effective for capturing high-quality aerial imagery, achieving high-resolution ground-level scans remains a challenge (SDA). Additionally, drone operations are often subject to strict regulations, requiring multiple permissions and licenses from relevant authorities, further complicating the process (SDA).

4.5 The Future

The short-term goals of DCU's digital twin project include expanding both the capability and scale of the DTs:

1. **Improvements in Data Visualisation:** Efforts are underway to develop more intuitive ways of visualising data within the DT. Raw data from IoT sensors, for example, a sound level of 56 dB or an air quality index (AQI) of 50, can be challenging to interpret when presented directly (SDK, SDJ). One proposed solution is to use visual cues, such as colour-coded building walls, to represent varying sound levels. Additionally, alternative visualisation techniques are being explored to better support users with visual impairments.
2. **Virtual Campus Experience:** A key short-term goal is to develop a fully immersive virtual campus experience utilising Unreal Engine. This would allow users to remotely explore and interact with the campus in a highly engaging, "gaming-like" environment, offering a more interactive alternative to traditional online university formats (SDA).
3. **Implementing Real-time Feedback Loops:** Currently, data flows periodically from various IoT sensors into the DT; however, the system lacks the ability to respond dynamically to real-time changes (SDA, SDK). Establishing real-time feedback loops, where the DT can actively respond to sensor inputs, is a key near-term objective.

The long-term goals of Smart DCU's DT project include:

4. **Knowledge Sharing:** Project stakeholders aim to share the lessons learned from the DT initiative with other universities and cities (SDA, SDK). This includes collaborating with external institutions to explore diverse use cases for DTs. There are also plans to scale the DT beyond the DCU campus to a city-wide implementation, demonstrating the broader feasibility and benefits of DT technology (SDK, SDJ).
5. **AI Integration:** A future goal is to integrate Large Language Models (LLMs) to enhance user interaction. Users would be able to ask questions about specific locations, receive directions through an avatar, and get contextual descriptions of their surroundings

(SDA). This capability could also support guided virtual tours, providing a personalised and intelligent campus experience.

6. **Cognitive Digital Twin:** A long-term ambition is to develop a cognitive DT capable of analysing real-time data, predicting future scenarios, and autonomously making decisions to optimise campus operations (SDK, SDJ). For instance, a cognitive DT could autonomously adjust traffic light timings to improve traffic flow at different times of the day (SDK).

These future goals highlight the ambitious scope of the DT project at DCU. As technological capabilities and resources evolve, the project aims to push the boundaries of what DT can achieve, particularly in critical areas such as risk management, emergency preparedness and response, accessibility, and sustainable campus management.

Note: Data was collected via interviews completed with key informants in DCU. The code used refers to:

SDA: Smart DCU Digital Twin Project Lead

SDK: Smart DCU Project Facilitator

SDJ: Smart DCU Researcher

5.0 Analysis of Primary Data

5.1 Introduction

To explore the practical applications of digital twin technology in emergency and risk management, a seminar was convened with members of the Emergency Management Institute Ireland (EMII): professionals from both the public and private sectors, representing law enforcement, fire services, defence, transport, maritime safety, and other critical infrastructure domains.

The primary objective of the session was to introduce participants to the concept of digital twins and demonstrate their potential to support a broad range of emergency management functions, including risk assessment, emergency preparedness, incident response, recovery, and training.

The seminar was designed to meet five key objectives:

1. Introduce Digital Twin technology and its relevance to emergency and risk management;
2. Showcase operational DT models to prompt discussion and practical reflection;
3. Explore potential applications, including operational use, inter-agency coordination, and systems integration;
4. Identify expected benefits as well as practical challenges to implementation;
5. Gather practitioner insights to inform future research and the development of scalable DT strategies.

To support deeper engagement with the final three objectives, exploring applications, identifying challenges and benefits, and collecting expert feedback, a series of structured focus group discussions were held following the seminar. These small-group sessions enabled participants to reflect more openly on the demonstrations, share operational experiences, and consider how digital twin technology might be adapted to meet the specific needs of their organisations.

Bringing together senior-level professionals from diverse disciplines was considered essential to ground the discussion in real-world operational needs. Their collective input is expected to help ensure that the future evolution of DT technology is both practically viable and aligned with the priorities of the wider emergency management ecosystem.

5.2 Focus Group Format & Participants

Following the seminar and live demonstrations of operational DT models, those developed for Dublin City University and Dublin Fire Brigade, a series of focus group discussions were held to encourage deeper exploration of the technology's potential in emergency and risk management.

Senior representatives from a broad range of Ireland's emergency, risk, and safety organisations took part in the discussions. These included participants from An Garda Síochána, Dublin Port, the Irish Defence Forces, the Fire Services, the Irish Coast Guard, the Prison Service, the Principal Response Agencies, Government Departments, and other key stakeholders.

Participants were divided into groups of five, with each group supported by a facilitator to guide the discussion. A consistent set of prompt questions was used across all groups to ensure comparability, while a free-flowing format encouraged open dialogue and the sharing of diverse perspectives.

5.3 Focus Group Framework and Discussion Prompts

To guide the post-seminar focus group sessions, participants were presented with a structured set of questions covering three key thematic areas: benefits, challenges, and application during emergencies. These questions were designed to encourage reflection on both the demonstrated features of digital twin technology and its potential future applications across various operational contexts.

1. Exploring the Benefits of Digital Twins

Participants were asked to reflect on how DTs could add value to their organisation or sector, both based on what they had seen in the seminar and from a broader, strategic perspective:

- **Q1:** Based on what you saw this morning, how could the introduction of a digital twin or digital twins benefit emergency, safety, or risk management in your organisation?

- **Q2:** Thinking more broadly, what benefits could digital twins bring to other industries or organisations?
- **Q3:** Apart from the features/elements you saw or heard about this morning, what else would be useful to have on a digital twin in order to increase risk, emergency, safety, security, or well-being on your site?

2. Identifying Implementation Challenges

This section explored the practical considerations involved in deploying DT technology, including organisational, technical, and cultural barriers:

- **Q4:** How easy or challenging would it be to implement a digital twin into your organisation or sector?

3. Evaluating Use During Emergencies

Finally, participants were asked to assess the potential of DTs to support real-time emergency response and decision-making:

- **Q5:** How effective do you think the features included in the digital twin (such as identification of hazards on site, use of each building, water sources, integration of planning documents, etc.) would be in helping decision-makers or emergency services during emergencies?

This framework helped surface insights related to operational readiness, cross-sector relevance, implementation feasibility, and real-world emergency scenarios, providing a rich basis for identifying next steps in DT development and deployment. Participants explored how digital twins can enhance areas such as training, pre-incident planning for emergencies, incident response through real-time information, and overall preparedness. They also considered secondary benefits such as improved legal compliance and insurance outcomes, while acknowledging hurdles related to technology adoption, digital literacy, bureaucracy, and the need for demonstrable utility at all organisational levels. The conversation further explored specific features of DTs, including hazard identification and the integration of planning documents, as well as their potential to significantly enhance decision-making during emergencies, alongside a realistic assessment of implementation complexities. The illustrations below present word frequency analyses of how respondents described potential uses (**Figure 11**) and challenges (**Figure 12**) related to the use and implementation of DT technology during the group discussions.

Figure 11: Word Frequencies of Uses of DT Suggested by Respondents during Focus Groups

Figure 12: Word Frequencies Related to Challenges to Implementations

5.4 Perceived Benefits

Participants acknowledged the transformative potential of digital twin technology to improve emergency and risk management across a wide range of organisations and sectors. The following key benefits emerged from the focus group discussions:

1. Enhanced Training and Preparedness

Digital Twins were widely recognised for their ability to improve training effectiveness, particularly through realistic, scenario-based simulations. These could support officer recruitment, development, and ongoing training, especially for those in command roles (GDR: Sp. 6, GDN: Sp. 2). DTs could also support structured training for Major Emergency Management (MEM) incidents, creating complex environments in which to rehearse command decisions and tactical responses (GDR: Sp. 2, GDG: Sp. 3). Moreover, the capacity to record these training scenarios enhances organisational preparedness and may serve as evidence of preparedness during post-incident reviews or inquiries (GDR: Sp. 4).

2. Improved Incident Management and Situational Awareness

During active incidents, DTs could offer real-time visualisations and spatial awareness, such as a “bird’s-eye view” of buildings or sites, which could significantly aid decision-making for incident commanders (GDR: Sp. 6, GDM: Sp. 6). Integration with body-worn cameras and sensor feeds would further enhance visibility. DTs may also prove highly valuable during large-scale public events or civil disturbances, enabling predictive deployment of resources (GDR: Sp. 6, GDM: Sp. 4).

In specialised scenarios such CBRN (Chemical, Biological, Radiological, and Nuclear) incidents, where threats are often invisible, DTs could track resource allocation and personnel movements with precision (GDN: Sp. 1, GDS: Sp. 2).

3. Effective Emergency Planning

DTs could support comprehensive pre-incident planning, including external emergency plans and response strategies for emerging risks (GDR: Sp. 6, GDM: Sp. 3). For organisations managing multiple or remote sites, DTs could provide a centralised crisis management platform with a live operational overview (GDG: Sp. 3).

This capability would also enhance tactical planning for sensitive operations such as seizures or law enforcement interventions, offering virtual familiarity with site layouts and access routes (GDR: Sp. 2).

4. Improved Understanding of Interdependencies

For complex environments, such as university campuses, industrial estates, ports, and hospitals, DTs can provide a systems-level view, illustrating how events in one area may affect others. For instance, a fire in one building may require evacuation plans that impact adjacent structures, traffic routes, or shared utilities (GDN: Sp. 3).

DTs would make it easier to visualise these interdependencies, which is especially critical for large-scale or hazardous operations, such as those in port environments (GDN: Sp. 2, GDG: Sp. 3).

5. Proactive Risk Assessment through Simulation

Participants saw value in using DTs to simulate a range of emergency scenarios, such as fires, active shooter incidents, or mass evacuations at large venues (GDN: Sp. 5, GDM: Sp. 1). These simulations help identify bottlenecks, validate response times, and test contingency plans under realistic conditions. For example, modelling a campus-wide evacuation, an operation rarely conducted in reality, could reveal critical shortcomings or overlooked vulnerabilities (GDN: Sp. 3).

6. Improved Inter-agency Coordination

Digital twins could act as a unified information environment, ensuring consistency of incoming data across multiple emergency services (GDR: Sp. 5, GDS: Sp. 2). Rather than relying solely on fragmented field reports, control rooms and command centres could access a shared, real-time overview of the situation, improving communication, coordination, and deployment decisions.

7. Legal and Compliance Advantages

The ability to document training, drills, and live incident responses within a DT system could provide an auditable record. This may prove crucial in formal reviews, inquiries, or court proceedings, where it can demonstrate procedural compliance, preparedness, and rationale for decisions made under pressure (GDR: Sp. 4, GDN: Sp. 1).

8. Enhanced Emergency Communication

Current emergency alert systems are often generic and not scenario-specific. DTs could offer a platform for more tailored communication, for instance, distinguishing between evacuation alerts during a fire and shelter-in-place instructions during a security threat (GDN: Sp. 3). Such systems would improve message clarity, reduce confusion, and deliver timely, audience-specific guidance to responders, staff, and the public.

9. Post-Incident Learning and Continuous Improvement

By acting as a centralised repository for incident data, DTs would support detailed post-incident analysis. This would enable emergency services to learn from past responses, refine procedures, and strengthen future preparedness strategies (GDR: Sp. 5, GDM: Sp. 2).

10. Inclusive Support for Vulnerable Individuals

Digital Twins have the potential to include layers of information about individuals with disabilities or additional needs. This could support targeted evacuation strategies and ensure inclusive emergency responses tailored to vulnerable populations (GDR: Sp. 2).

Additional Benefits for Wider Industry Applications

11. Insurance and Risk Profiling

For large organisations, the ability to demonstrate robust emergency preparedness and detailed incident data through DTs may lead to improved risk profiles. This, in turn, could support efforts to negotiate more favourable insurance premiums (GDR: Sp. 1, GDM: Sp. 5).

12. Optimised Facilities Management

Digital Twins enable real-time monitoring of facilities, enhanced after-hours security, and rapid response to on-site events across multiple locations (GDR: Sp. 4). This would significantly increase the efficiency and responsiveness of facilities management operations.

As summarised in **Figure 13,** the focus groups identified not only the benefits of using Digital Twins (DTs) in risk and emergency management but also several challenges. These challenges are outlined in the section below.

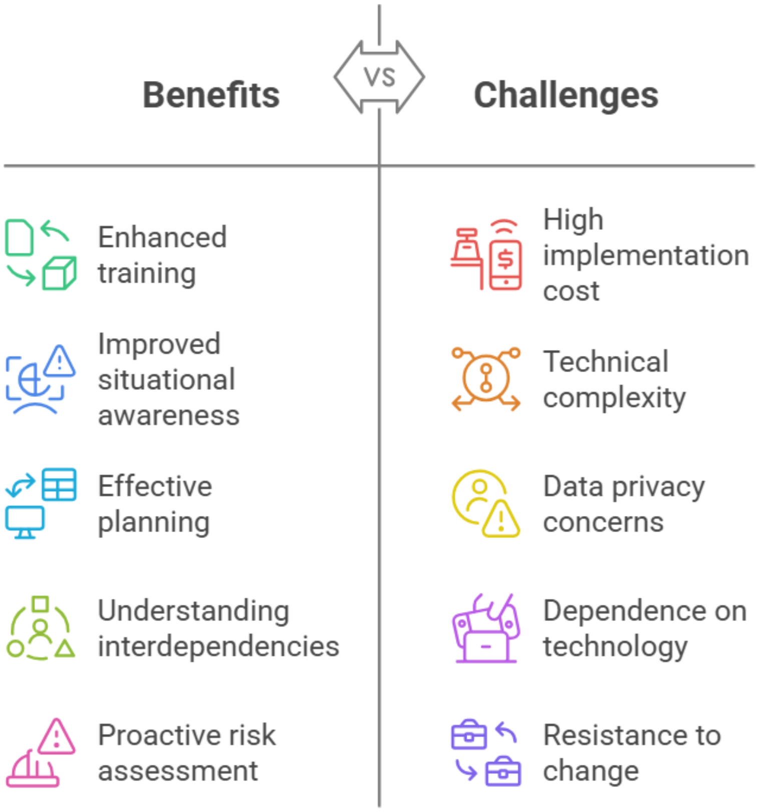

Figure 13: Key Benefits and Challenges of Digital Twin

5.5 Perceived Challenges to DT Implementation

While participants recognised the significant potential of digital twin technology, they also identified several challenges and barriers to successful implementation. These concerns reflect both strategic and operational realities across diverse organisations:

1. Practicality and Usability

For DT systems to be adopted and sustained, they must be practical, intuitive, and solve real problems faced by operational personnel (GDR: Sp. 1, GDS: Sp. 2). A user-friendly interface is essential. In parallel, training must not only be comprehensive but also ongoing, ensuring that users remain confident and competent over time (GDM: Sp. 3, GDG: Sp. 6).

2. Digital Literacy and Resistance to Change

Many organisations face varying levels of digital literacy, particularly across ranks or departments. Resistance to adopting new technologies can stem from unfamiliarity, fear of change, or concern over job relevance (GDR: Sp. 6, GDN: Sp. 3, GDS: Sp. 2). Gradual, well-supported implementation and leadership endorsement are essential to overcoming this barrier.

3. Data Prioritisation and Relevance

Determining which data is necessary, who needs access, and when it should be delivered is a critical challenge, especially in multi-site or multi-agency contexts (GDR: Sp. 1, GDM: Sp. 2). Without clear data governance protocols, the system risks either overwhelming users or failing to deliver useful information.

4. Impact on Accountability and Inquiries

The ability of DTs to record and log all activity during training and live incidents enhances transparency and supports learning (GDR: Sp. 5). However, this level of scrutiny may also raise concerns about exposure to legal or reputational consequences in the event of human error, potentially discouraging honest engagement or uptake.

5. Cost and Return on Investment (ROI)

Implementing, maintaining, and scaling DT systems requires significant financial investment (GDR: Sp. 3, GDS: Sp. 2). For private organisations in particular, justifying the expenditure can be difficult without a clear, demonstrable ROI (GDN: Sp. 3). Long-term value may depend on successful integration into core operations.

6. Risk of Operational Interference

Real-time access to DT data by off-site command units raises concerns about interference with on-the-ground decision-making (GDR: Sp. 4). There is a risk that remote actors could undermine incident commanders, creating confusion or delays during fast-moving emergencies.

7. Information Overload and Response Efficiency

While DTs are capable of processing vast datasets, this information must be filtered and tailored to specific user roles to avoid cognitive overload (GDR: Sp. 2). Frontline responders need incident-specific information, while commanders may require a broader overview. Rapid access to concise, role-appropriate data is critical during emergencies.

8. Data Security and Privacy Compliance

DTs process sensitive, often real-time data that may include personal identifiers or protected information. Ensuring compliance with data protection regulations (such as GDPR) is essential (GDN: Sp. 3, GDM: Sp. 4, GDG: Sp. 2). Robust data governance and cybersecurity protocols must be in place to prevent breaches or misuse.

9. Data Ownership and Inter-Organisational Sharing

Clear accountability for maintaining, updating, and verifying DT data is essential to ensure system reliability (GDM: Sp. 4, GDG: Sp. 4). In multi-agency environments, information-sharing agreements must define access rights, update responsibilities, and interoperability standards (GDM: Sp. 1).

10. Integration with Legacy Systems and Organisational Readiness

The complexity of integrating DT platforms with existing systems and databases can pose significant technical and financial barriers (GDG: Sp. 3). Additionally, the willingness of key personnel, especially those in senior or decision-making roles, to adopt and use DTs plays a pivotal role in successful implementation (GDM: Sp. 1).

11. External Access and Volunteer Coordination

During emergencies, access for external support teams or volunteers may be essential. However, providing secure and rapid access to DT systems, while adhering to necessary verification, firewall, or authentication protocols, can be cumbersome when time is critical (GDG: Sp. 3, GDG: Sp. 5).

12. Bureaucracy and Organisational Inertia

Long-standing bureaucratic processes can inhibit the adoption of new technologies, particularly in traditional or hierarchical organisations (GDR: Sp. 4). Overcoming such inertia requires not only leadership support but also strategic change management efforts.

5.6 Future Opportunities for Digital Twin (DT) Implementation Across Sectors

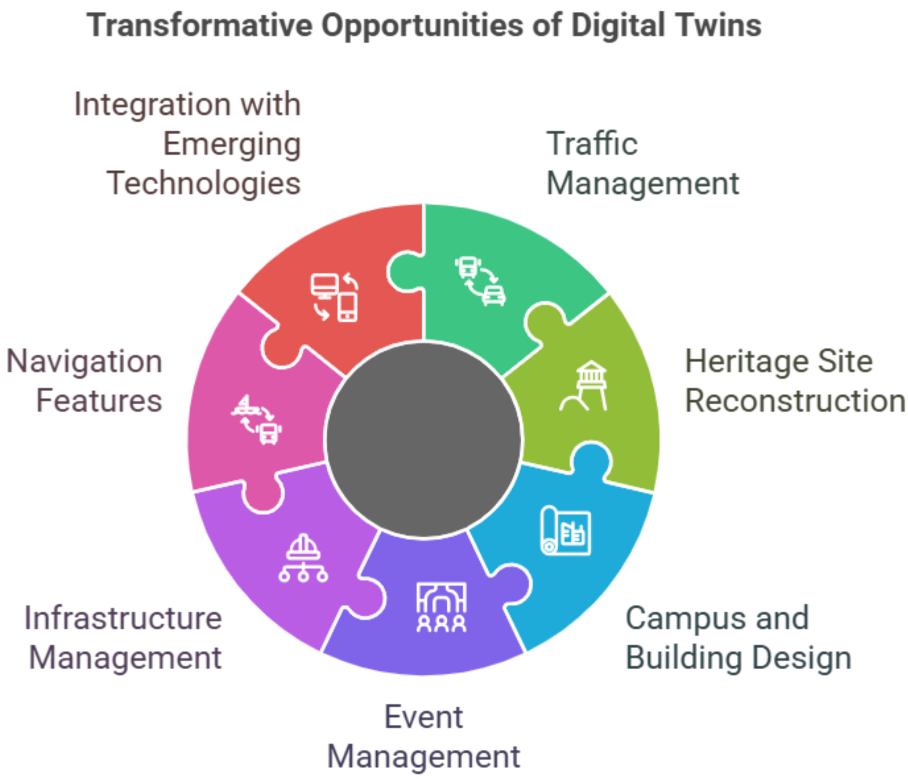

Figure 14: Opportunities for DT Implementation

In addition to their value in emergency and risk management, DTs have significant potential to transform operations across a wide range of sectors. Participants identified several promising applications for future DT deployment, highlighting both operational enhancements and opportunities for innovation:

1. Traffic and Transport Management

Integrating real-time traffic data into DT systems could enhance both daily traffic control and emergency response logistics (GDR: Sp. 2). DTs could simulate road congestion and predict delays, enabling better planning for route optimisation during incidents and large-scale evacuations.

2. Heritage and Cultural Site Preservation

DTs could play a critical role in the preservation and restoration of heritage sites. By creating detailed digital replicas of historic landmarks, organisations can facilitate accurate reconstruction following damage from fire, natural disasters, or other incidents (GDR: Sp. 3). A global example includes the digital modelling of Notre Dame Cathedral, which guided its post-fire restoration.

3. Campus and Building Design Optimisation

On large campuses or building complexes, DTs could track footfall, space usage, and occupant behaviour (GDN: Sp. 3). This data may be used to inform the design of future buildings, improve crowd management, and optimise layouts for accessibility, energy efficiency, or emergency evacuation (GDR: Sp. 2).

4. Event and Venue Management

For high-capacity events such as concerts, sports fixtures, or public demonstrations, DTs offer significant planning and operational advantages. Real-time data would identify crowd density hotspots and facilitate proactive interventions, including evacuation planning or medical response (GDR: Sp. 4, GDM: Sp. 2).

5. Complex Infrastructure Planning

DTs could support emergency response and operational continuity in critical infrastructure environments, such as railways, ports, and airports, by mapping optimal access routes, identifying risk zones, and integrating with control systems to visualise disruptions or threats (GDR: Sp. 5).

6. Custom Navigation and Communication Features

Participants suggested expanding DT functionality to include bespoke tools tailored to organisational needs. Examples include navigation support (e.g., directing staff or responders from one location to another within a site) and two-way communication features between field personnel and command centres (GDM: Sp. 4).

7. Integration with Emerging Technologies

The transformative potential of DTs would be amplified through integration with emerging technologies such as AI, Augmented/Virtual Reality (AR/VR), and IoT. These integrations could support immersive training environments, intelligent scenario forecasting, and automated sensor-driven responses (GDN: Sp. 4).

Additional Concepts for Future Expansion

Several forward-looking ideas were proposed by participants to unlock new capabilities and user benefits through DT technology:

- **Mobile Phone Integration**: With appropriate permissions and privacy safeguards, DTs could incorporate anonymised real-time location data from mobile devices to map the movement of staff and public occupants during incidents.
- **Emergency Caller GPS Pinpointing**: Linking DTs to emergency call systems could enable accurate geolocation of individuals, even inside complex or multistorey environments, significantly improving emergency response efficiency.
- **Mobile Alerts for Vulnerable Populations**: A DT-linked mobile application could allow individuals with additional needs or specific health conditions to alert emergency services with their exact location and needs, supporting a more inclusive and responsive emergency system (GDR: Sp. 2).

These insights reflect the growing recognition of DTs not only as risk and emergency management tools but as strategic assets for urban management, safety planning, and organisational innovation. The opportunity now lies in aligning technology development with real-world needs across both public and private sectors.

5.7 Conclusion

The focus group discussions underscored the significant potential of DTs to transform emergency and risk management, as well as deliver value across a broad range of sectors and industries. Participants highlighted key benefits, including enhanced training and preparedness, improved incident management, more effective emergency planning, and more informed and intelligent resource allocation. However, they also raised concerns regarding practical implementation, particularly around usability, data privacy and security, and challenges linked to digital literacy and organisational resistance to change. To support successful adoption, pilot initiatives and a phased rollout approach, underpinned by robust user training, will be essential. Ultimately, the effectiveness of DT implementation will depend on a deep understanding of end-user needs, a commitment to intuitive design, and a strategic focus on overcoming cultural and technical barriers.

Key:

GDR: Group Discussion roundtable facilitated by RH

GDN: Group Discussion roundtable facilitated by NR

GDM: Group Discussion roundtable facilitated by MOD

GDS: Group Discussion roundtable facilitated by SJ

GDG: Group Discussion roundtable facilitated by GB

6.0 Technical Review

Digital Twin (DT) technologies have rapidly evolved, with a range of advanced platforms now supporting applications across diverse sectors, including infrastructure, manufacturing, energy, and asset management. As organisations increasingly recognise the value of virtual replicas for monitoring, simulation, and predictive analytics, selecting the appropriate DT tools becomes critical for successful implementation. This chapter provides a comparative evaluation of leading digital twin platforms offered by major technology companies, analysing their core features, strengths, and limitations in the context of real-world use.

Following this market overview, the chapter outlines the rationale for selecting Bentley Systems as the digital twin partner for the DT4EM project. The decision was informed by Bentley's alignment with the project's strategic goals, its integrated toolchain for infrastructure-focused DTs, and its proven capabilities in Smart City applications. Through this analysis, the chapter highlights the importance of matching platform capabilities with project requirements and long-term vision.

6.1 Evaluation of Current Digital Twin Tools and Software

Many technology providers offer comprehensive tools for developing digital twins, each designed to address specific industry needs and applications. The following are some of the most widely adopted digital twin platforms and their key characteristics:

1. Siemens Digital Twins: Siemens provides a range of software solutions for complete product lifecycle management (PLM). The platform offers real-time collaboration among different teams and complete integration with other Siemens tools and third-party applications. A significant strength is its ability to enable virtual design, simulation, and performance measurement of products before physical production begins, thereby accelerating the time-to-market (Siemens, 2025).

Some of the benefits are its ability to offer comprehensive PLM capabilities and seamless integration with industry tools. Some of the drawbacks include the high cost of using the suite of products and the specific skillset requirement for working with its tools.

2. Microsoft Azure Digital Twins: Microsoft offers a robust DT solution with strong cloud support and integration. The DT service is offered as part of its Azure suite of products and utilises Digital Twin Definition Language (DTDL) to create custom domain models for any connected environment. A significant strength is its scalability and deep cloud integration capabilities with other Microsoft products (Microsoft, 2025). Some of the cons include the steep pricing structure of its tools and the strong technical expertise required to work with its platform.

3. IBM Digital Twins: Through the Maximo Asset Monitor, IBM offers a sophisticated DT system for monitoring the health and performance of various assets. The platform provides real-time visibility, anomaly detection, current and historical data trends, and AI-driven actionable insights for devices and assets through an interactive dashboard. With capabilities such as asset tracking, maintenance, and continuous monitoring, it supports comprehensive asset management functions (IBM, 2025). The IBM Maximo Asset Monitor is widely used in industries such as energy, aerospace, rail, and other asset-intensive sectors.

Some of the benefits include a robust solution for asset health insights and complete asset management, as well as integration with many other IBM tools. Some of the drawbacks include initial setup complexity, a steep learning curve, and the specialised skillset requirements for working with its platform.

4. Bentley Systems Digital Twins: Bentley offers innovative products for DTs within the infrastructure and Smart Cities domain. Its products provide flexible and seamless data management capabilities, with the integration of BIM data, open libraries, change tracking, visualisation, and AI-powered insights. Bentley's iTwin platform stands out significantly for infrastructure projects, offering efficient methods for data handling and integration (Bentley Systems, 2025).

Some of the advantages of using Bentley's tools are their ability to integrate GIS and BIM data extensively into the DT and their strong support for the infrastructure, construction, and engineering industries. Some of the disadvantages include the need for familiarity with Bentley's ecosystem of products and its niche focus in selected industries.

5. GE Digital Twins: GE provides comprehensive DT solutions for the manufacturing, energy, and oil and gas industries. It offers asset management DTs for critical assets with dynamic visualisation of data to support operations and maintenance, grid DTs for real-time views of end-to-end networks and grid operations, and process DTs for optimal process execution in manufacturing (GE Vernova, 2025).

Some of the benefits of using GE's DTs include robust support for industrial asset performance monitoring, advanced analytics, and predictive maintenance capabilities. Additionally, GE brings strong domain expertise in the energy and utilities sectors, offering real-time analytics and accurate asset representation. A significant drawback is that the platform is primarily designed for large-scale industrial applications and requires specialised technical expertise for its use.

6. PTC Digital Twins: PTC offers a leading Industrial IoT (IIoT) platform for developing IoT applications. The platform offers powerful tools and applications that accelerate the development and scaling of IIoT solutions, including AR experiences. PTC's ThingWorx facilitates the gathering of real-time insights from complex IIoT data, allowing operational optimisation and issue prevention. The platform has extensive applications in the service, manufacturing, and engineering industries (PTC Inc., 2025).

Some of the pros of using PTC's platform include strong support for IoT integration and data analytics, rapid application development, efficient data integration, and its strong position as a leader in IIoT deployment. A notable drawback is its complex and steep pricing structure.

7. Ansys Digital Twins: Ansys offers Twin Builder, a DT solution that excels in multi-domain system modelling, enabling the creation of complex systems using various languages and domains. Ansys Twin Builder works with its physics-based simulation technology to embed detailed 3D simulations as Reduced Order Models (ROMs) (Ansys, 2025).

Some of the advantages of working with the Twin Builder include its deep physics-based modelling capabilities and efficient use of ROMs, which enable high-fidelity, rapid simulation. A major drawback is the need for specialised platform expertise for use, and it can be expensive to use.

6.2 Reasons for Choosing Bentley Systems

It was clear that Bentley Systems was selected as the strategic partner for the DFB and DCU projects due to its strong alignment with the goals and technical requirements of both projects. Several key factors informed the decision to adopt Bentley's suite of DT tools:

1. Alignment with Project Goal: Bentley emerged as the preferred technology provider on both projects due to the strong alignment between its product offerings and the overarching objectives of the projects. As a recognised leader in infrastructure and Smart City DT solutions, Bentley provided a mature, scalable platform that supported both the immediate technical needs and the long-term vision of the projects.

2. End-to-end DT Capabilities: Bentley offered a comprehensive, full-stack suite of DT tools, ranging from the initial capture and integration of point clouds and BIM data to processing and visualisation of fully realised DTs. This seamless workflow reduced integration complexity and enabled faster and efficient development of DTs.

3. Technical Support and Flexibility: Bentley provides strong and reliable technical support, which proved critical during both projects. Additionally, the ability to accommodate edge cases and adapt the tools to unique project needs demonstrated the platform's flexibility and suitability for research-driven development.

4. Ease of Use: The projects' research and development teams found Bentley's software to be intuitive, requiring a short learning curve, which allowed the teams to become proficient quickly. This contrasts with some of the other DT platforms, which often require specialised expertise or steep learning curves before working with their tools.

7.0 Recommendations for the Future: A Unified DT Initiative for Emergency Management

7.1 Introduction: Towards DT4EM

This concluding chapter recommends combining the two pioneering Digital Twin (DT) projects explored in this report, Dublin Fire Brigade's DTER (Digital Twin for Emergency Response) and Smart DCU's immersive campus-wide DT platform, into a unified, collaborative initiative: DT4EM (Digital Twins for Emergency Management). By leveraging the complementary strengths of each project, DT4EM can become a nationally, or even internationally, significant demonstration of how advanced digital technologies can enhance resilience and transform emergency management: risk assessment, risk management, planning, preparedness, response, and recovery.

7.2 Rationale for Integration

The DTER project by DFB excels in pre-incident planning and operational deployment, focusing on high-risk sites, integrating drone-generated 3D models, BIM data, and GIS layers into an accessible platform. Smart DCU's Digital Twin, meanwhile, demonstrates sophisticated real-time sensor integration, immersive visualisation, and innovative use cases including accessibility, navigation, and campus safety.

A unified DT4EM project would:

- Combine immersive scenario planning and pre-fire intelligence from DFB with real-time campus-wide analytics from DCU.
- Enhance interoperability and knowledge exchange between emergency responders, technologists, and academic researchers.
- Facilitate cross-sectoral training and multi-agency coordination.
- Deliver a scalable model for other urban areas, public safety agencies, and emergency responders.

7.3 Key Technical and Strategic Recommendations for DT4EM

7.3.1 Pre-Incident/Pre-Fire Planning Enhancements

High-Resolution 3D Site Modelling: Capture highly detailed spatial and structural information of critical infrastructure and environmental characteristics of the campus using drone photogrammetry and iTwin Capture Modeller. This allows responders to visualise and understand all elements of a site before arriving: buildings, roads, storage tanks, amenities, energy supply, adjacent land use, etc.

Dynamic Risk Mapping: Continuously update fire risk profiles using real-time and static data sources. Include locations of fire hydrants, gas lines, fire alarm panels, and known hazardous materials.

Evacuation Modelling: Employ advanced simulation engines (e.g., Unreal Engine) to test and validate building evacuations under varying conditions, accounting for bottlenecks and populations with additional needs.

Access and Entry Point Analysis: Use BIM data to identify optimal firefighter entry routes, interior navigation paths, and external staging areas. Include scenario-based assessments of access restrictions due to debris or structural failure.

7.3.2 Real-Time Data Integration

Ambient Data: Stream ambient data such as heat, gas, and smoke detection from DCU's IoT sensor networks directly into the DT environment.

Emergency Services: Synchronise GPS and telemetry data from emergency service vehicles, enabling real-time tracking and deployment coordination.

Dashboards: Build intuitive dashboards in OpenCities Planner that layer operational data over 3D cityscapes, giving decision-makers up-to-the-second situational awareness.

7.3.3 Training and Immersive Simulation

Scenarios: Use VR to replicate reasonable worst-case scenarios (RWCS) and high-impact, low-probability (HILP) scenarios for training, such as mass casualty incidents, industrial fires, transport incidents, and significant flooding.

Trainees: Provide repeatable, immersive experiences that allow trainees to interact with realistic environments, thereby enhancing muscle memory and cognitive response.

AI Inputs: Introduce AI to dynamically modify scenarios, simulating unpredictable developments such as secondary explosions or blocked escape routes.

7.3.4 Multi-Agency Coordination and Communication

Access to Sensitive Data: Create a unified DT platform accessible by all emergency response and infrastructure stakeholders, with role-based permissions to control access to sensitive data.

Multi-Agency: Support multi-agency simulations and live responses by sharing up-to-date models, maps, and data feeds in a shared virtual environment.

Communication: Formalise communication protocols and Standard Operating Procedures (SOPs) for how agencies interact through the DT during major incidents and exercises.

7.3.5 Data Management and Governance

Hybrid Architecture: Implement a hybrid architecture that allows agencies to manage their own data sets while contributing to a centralised DT interface.

Governance: Design robust governance policies around data sharing, including anonymisation protocols, user authentication, and audit logs.

Updates: Schedule routine updates of 3D models, infrastructure layouts, and system integrations, ensuring accuracy during real-world deployments.

7.3.6 Scalability and National Significance

Demonstrator Model: Develop DT4EM as a demonstrator project with the capacity to inform national frameworks on emergency preparedness and resilience.

Showcase: Showcase interoperable, smart emergency management as a model for replication in other jurisdictions.

Funding: Seek funding from national innovation schemes and EU programmes, such as the EU Civil Protection Mechanism, to support development and scale-up.

7.4 Suggested Features to Integrate from Smart DCU into DT4EM

Autism-Friendly Navigation Tools: Apply inclusive design principles to emergency wayfinding interfaces, ensuring clarity, simplicity, and reduced sensory overload.

Sound and Air Quality Monitoring: Feed ambient data into the DT to forecast hazardous conditions, adjust response strategies, and inform protective equipment choices.

Avatar-Guided Tours and Exploration: Offer digital walkthroughs of key infrastructure for new recruits, visiting responders, or remote briefings.

Energy Usage and System Status Layers: Use facilities data to detect operational anomalies, such as HVAC failures or power outages, which could escalate emergency conditions.

7.5 Additional Use Cases Identified from Focus Groups for Campus DT

Asset Tracking and Inventory Management: Implement RFID or GPS tagging for critical campus assets such as defibrillators, emergency kits, fire extinguishers, and hazardous materials. Enable real-time tracking of these items' locations, conditions, and expiration or service dates through the DT interface.

Crowd Monitoring and Behaviour Prediction: Integrate data from CCTVs, Wi-Fi pings, and entry systems to monitor crowd densities in lecture halls, cafeterias, or sports/event venues. AI models can predict bottlenecks, detect panic-like behaviour, and support decisions on crowd control or evacuation.

Utility Monitoring and Failure Forecasting: Use IoT-connected meters and sensors in water, electrical, and HVAC systems to predict malfunctions or inefficiencies. Alerts can be generated in the DT platform to trigger early maintenance, thereby reducing risks such as power outages or system overloads during both emergencies and everyday operations.

Climate Risk Scenarios: Utilise meteorological and climate modelling tools to simulate the impact of floods, high winds, or heatwaves on buildings, critical infrastructure, and access routes across campus. Enable preparedness planning based on simulated impact zones.

Public Health Monitoring: Use CO2 sensors, motion detectors, and temperature sensors to measure indoor air quality and occupancy levels. These metrics can support decisions around ventilation improvements or social distancing during pandemics or other public health events.

Accessibility and Inclusion Features: Model emergency evacuations involving individuals with additional needs. Simulate scenarios to identify gaps in accessible routes or procedures and propose targeted improvements (e.g., ramps, refuge points, visual alarms).

Communications Infrastructure Resilience: Digitally map communications assets such as repeaters, Wi-Fi nodes, and emergency radio systems. Identify potential points of failure and simulate their impact on command-and-control communications in a crisis.

Cybersecurity Breach Simulations: Introduce cyber-risk modelling scenarios, testing the DT system's ability to support continuity of operations during IT system outages, data breaches, or ransomware attacks. Include simulations of system lockdown protocols and recovery workflows.

Virtual Inductions and Familiarisation Tours: Develop interactive modules where students, faculty, or responders can explore the campus DT. Highlight safety features, emergency exits, and procedures in an engaging format to improve situational awareness and preparedness.

Post-Incident Review and Debriefing: Record DT-based emergency simulations and real-time data streams during live incidents. Enable playback and annotation to support training, learning, and investigation processes across disciplines and agencies.

7.6 Conclusion

DT4EM represents a logical and strategic synthesis of two leading-edge DT projects in Ireland. Together, they offer an unparalleled opportunity to reimagine how digital tools support emergency management. This combined initiative will bridge operational reality with technological capability, improving preparedness, resilience, and ultimately, public safety. With strong governance, stakeholder commitment, and continued innovation, DT4EM can serve as a flagship for the next generation of digitally enabled emergency management systems.

8.0 References

Abdrakhmanova, K.N., Fedosov, A.V., Idrisova, K.R., Abdrakhmanov, N.K. and Valeeva, R.R., 2020, May. Review of modern software complexes and digital twin concept for forecasting emergency situations in oil and gas industry. *IOP Conference Series: Materials Science and Engineering* (Vol. 862, No. 3, p. 032078). IOP Publishing.

Ahmed and Currie, R. 2024. Smarter Cities: Exploring the Applications of Emergency Management through Digital Twin Technology. *ACSA Annual Meeting Proceedings*, [online] pp.157–163. doi:https://doi.org/10.35483/acsa.am.112.22.

Alibrandi, U. 2022. Risk-Informed Digital Twin of Buildings and Infrastructures for Sustainable and Resilient Urban Communities. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 8*(3). doi:https://doi.org/10.1061/ajrua6.0001238.

Altair. (2022). *Digital Twin Summary Report*. [online] Available at: https://altair.com/resource/digital-twin-summary-report

Amazon Web Services, Inc. (2024). *What is Digital Twin Technology? - Digital Twin Technology Explained - AWS*. [online] Available at: https://aws.amazon.com/what-is/digital-twin/

Ansys, 2025. *Digital Twin Simulation-Based Software.* [online] Available at: https://www.ansys.com/products/digital-twin

Argolini, R., Bonalumi, F., Deichmann, J. and Pellegrinelli, S., 2023. *Digital twins: The key to smart product development*. [online] Available at: https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/digital-twins-the-key-to-smart-product-development

Ariyachandra, M.R.M.F. and Wedawatta, G. 2023. Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts. *Sustainability*, [online] 15(15), p.11910. doi: https://doi.org/10.3390/su151511910

Ayukawa, R. and Miyosawa, T., 2022. Research and development of Digital twin system for visualizing disaster prevention information in Chino city. *ITE Technical Report; ITE Tech. Rep., 46*(10), pp.411-412.

Bentley Systems, 2025. *iTwin Platform – Infrastructure Digital Twins.* [online] Available at: https://www.bentley.com/software/itwin-platform/

Bian, M., Su, Y. and Cheng, C., 2022, November. Simulation system design and application analysis of power intelligent emergency repair scene based on digital twin technology. *In: International Symposium on Robotics, Artificial Intelligence, and Information Engineering (RAIIE 2022)* (Vol. 12454, pp. 7-14). SPIE.

Brucherseifer, E., Marquard, M., Hellmann, M., & Tundis, A., 2025. *A Data Taxonomy Towards the Applicability of the Digital Twin Conceptual Framework in Disaster Management*. arXiv preprint arXiv:2503.00076. Available at: https://arxiv.org/abs/2503.00076

Brucherseifer, E., Winter, H., Mentges, A., Mühlhäuser, M. and Hellmann, M., 2021. Digital Twin conceptual framework for improving critical infrastructure resilience. *at-Automatisierungstechnik, 69*(12), pp.1062-1080.

Capgemini. (2022). *Digital Twins*. [online] Available at: https://www.capgemini.com/insights/research-library/digital-twins/

Celeste, E. and Dominioni, G., 2024. Digital and green: reconciling the EU twin transitions in times of war and energy crisis. *In: Research Handbook on Post-Pandemic EU Economic Governance and NGEU Law,* pp. 161-178. Edward Elgar Publishing.

Cepolina, F. and Cepolina, E.M., 2022, August. Simulation and digital twin of a robotic sanitizing process of environments at risk during the pandemic. In: *Climbing and Walking Robots Conference,* pp. 501-512. Cham: Springer International Publishing.

Chang, X., Zhang, R., Mao, J. and Fu, Y., 2024. *Digital Twins in Transportation Infrastructure: An Investigation of the Key Enabling Technologies, Applications, and Challenges*. IEEE Transactions on Intelligent Transportation Systems, 25(7), pp. 6449–6471. doi:10.1109/TITS.2024.3401716

Cheng, R., Hou, L. and Xu, S. 2023. 'A Review of Digital Twin Applications in Civil and Infrastructure Emergency Management'. *Buildings, 13*(5), p. 1143. Available at: https://doi.org/10.3390/buildings13051143.

Ding, Y., Zhang, Y. and Huang, X., 2023. Intelligent emergency digital twin system for monitoring building fire evacuation. *Journal of Building Engineering*, *77,* p.107416.

Doğan, Ö., Şahin, O. and Karaarslan, E., 2021. *Digital twin based disaster management system proposal: DT-DMS*. Journal of Emerging Computer Technologies, 1(2), pp.25-30.

Duan, C., Zhang, Z., Zhao, L. and Yu, Y., 2024. Reliability and risk assessment of digital twin system based on improved failure mode and effects analysis. *The International Journal of Advanced Manufacturing Technology*, pp.1-19.

Dublin City Fire Brigade, (2023). *Dublin City Fire Brigade Annual Report 2023* [pdf] Dublin City Council. Available at: https://www.dublincity.ie/sites/default/files/2024-05/dfb-2023-annual-report-low-res-1_0.pdf

Dublin City Fire Brigade, (2024). *What Dublin Fire Brigade Do.* [online] Dublin City Council. Available at: https://www.dublincity.ie/residential/dublin-fire-brigade/what-dublin-fire-brigade-do

Dublin City University, (2023). *DCU launches new quiet space informed by autism-friendly university design*. [online] DCU. Available at: https://www.dcu.ie/commsteam/news/2023/dec/dcu-launches-new-quiet-space-informed-autism-friendly-university-design

Dublin City University, n.d. *DCU Autism Friendly.* [online] Available at: https://www.dcu.ie/autism-friendly

EY, (2024). *Cloud and data are the cornerstone of Gen AI's success: EY-FICCI Cloud Report*. [online] Available at: https://www.ey.com/en_in/technology/digital-twins-creating-intelligent-industries

Fan, C. and Mostafavi, A., 2020, November. Disaster City Digital Twin: A Vision of Integrating Human and Artificial Intelligence for Urban Resilience. In: *Joint International Resilience Conference,* November.

Fan, C., Jiang, Y. and Mostafavi, A., 2020. Social sensing in disaster city digital twin: Integrated textual-visual-geo framework for situational awareness during built environment disruptions. *Journal of Management in Engineering, 36*(3), p.04020002.

Fan, C., Zhang, C., Yahja, A. and Mostafavi, A. 2019. Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management, 56*, p.102049. doi: https://doi.org/10.1016/j.ijinfomgt.2019.102049

Fargusson, S., Fisher, R., Farshadmanesh, P., Bui, H. and Mohaghegh, Z., 2023. Theoretical Foundation of Modeling Human-Digital Twin Interactions and Their Impacts on Safety Risk in Nuclear Power Plants.

Fernandez, J.B., Osadcha, I., Jurelionis, A., Mahon, K., O'Connor, N.E. and Ali, M.I., 2024. *Smart DCU Digital Twin: Towards Autism-Friendly Universities*. In: 2024 IEEE Smart World Congress (SWC), Nadi, Fiji, pp.2002–2009. IEEE. doi:10.1109/SWC62898.2024.00308.

Fisher, R., Fargusson, S., Mitstifer, J., Beal, J., Bui, H., Farshadmanesh, P., Sakurahara, T., Reihani, S., Kee, E. and Mohaghegh, Z., 2023, October. On Modeling Human-Digital Twin Interactions and their Safety Risk Impact in Nuclear Power Plants. In: *Probabilistic Safety Assessment and Management (PSAM) International Topical Meeting on Artificial Intelligence (AI) and Risk Analysis*.

Ford, D.N. and Wolf, C.M. 2020. Smart Cities with Digital Twin Systems for Disaster Management. *Journal of Management in Engineering, 36*(4), p.04020027. doi:https://doi.org/10.1061/(asce)me.1943-5479.0000779.

Gawde, P., (2023). *Dublin City University (DCU) Campus Serves as Testbed for Exploring AI and Digital Twins for Smart City Innovations*. [online] Bentley Systems. Available at: https://www.bentley.com/wp-content/uploads/2023-year-in-infrastructure-founders-honors-dublin-city-university-final.pdf

Ge, C. and Qin, S., 2024. *A Generative City Digital Twin System for Flooding Emergency Management in Smart City*. In: *2024 29th International Conference on Automation and Computing (ICAC)*, Sunderland, UK, 28–30 August 2024. Piscataway, NJ: IEEE, pp. 1–6. doi:10.1109/ICAC61394.2024.10718830

GE Vernova, 2025. *Digital Twin – GE Vernova.* [online] Available at: https://www.gevernova.com/software/innovation/digital-twin-technology

Ghita, M., Siham, B., Hicham, M. and Hafid, G., 2022. Artificial and Geospatial Intelligence Driven Digital Twins' Architecture Development Against the Worldwide Twin Crisis Caused by COVID-19. In: *Geospatial Intelligence: Applications and Future Trends*, pp.79-104.

Grieves, M., 2014. Digital twin: manufacturing excellence through virtual factory replication. *White paper, 1*(2014), pp.1-7

Guo, T.N., 2022, September. Robust Q-learning for fast and optimal flying base station placement aided by digital twin for emergency use. In: *2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall)* (pp. 1-6). IEEE.

Guo, Y., Yan, A. and Wang, J., 2021, December. Cyber security risk analysis of physical protection systems of nuclear power plants and research on the cyber security test platform using digital twin technology. In: *2021 International Conference on Power System Technology (POWERCON),* pp. 1889-1892. IEEE.

Ham, Y. and Kim, J., 2020. Participatory sensing and digital twin city: Updating virtual city models for enhanced risk-informed decision-making. *Journal of Management in Engineering, 36*(3), p.04020005.

Henriksen, H.J., Schneider, R., Koch, J., Ondracek, M., Troldborg, L., Seidenfaden, I.K., Kragh, S.J., Bøgh, E. and Stisen, S. 2022. A New Digital Twin for Climate Change Adaptation, Water Management, and Disaster Risk Reduction (HIP Digital Twin). *Water, 15*(1), p.25. doi:https://doi.org/10.3390/w15010025.

Hezam, I.M., Ali, A.M., Sallam, K., Hameed, I.A. and Abdel-Basset, M., 2024. Digital twin and fuzzy framework for supply chain sustainability risk assessment and management in supplier selection. *Scientific Reports, 14*(1), p.17718.

Hong, Y.Y. and Apolinario, G.F.D., 2022. Ancillary services and risk assessment of networked microgrids using digital twin. *IEEE Transactions on Power Systems, 38*(5), pp.4542-4558.

IBM (2022). *What Is a Digital Twin.* [online] IBM. Available at: https://www.ibm.com/topics/what-is-a-digital-twin

IBM, 2025. *IBM Maximo: Enterprise asset management & digital twin solutions.* [online] Available at: https://www.ibm.com/products/maximo

Ibrahim, O. 2019. Digital twin technology: A study of differences from simulation modelling and applicability in improving risk analysis. *Unit.no.* [online] doi:http://hdl.handle.net/11250/2626223.

Isaev, A.V., Nefed'ev, A.I. and Isaev, I.A., 2022, May. Digital twin technologies for diesel generator sets in backup and emergency power supply systems. In: *2022 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, pp. 1079-1084. IEEE.

Jaribion, A., Khajavi, S.H., Öhman, M., Knapen, A. and Holmström, J. (2020). A Digital Twin for Safety and Risk Management: A Prototype for a Hydrogen High-Pressure Vessel. In: *Designing for Digital Transformation. Co-Creating Services with Citizens and Industry*, pp.369–375. doi:https://doi.org/10.1007/978-3-030-64823-7_34.

Johansson, F., Göransson, E., Nathorst-Westfelt, P., Jongeling, R., Claeson-Jonsson, C., Tomar, R., Gonçalves, J., Chacón Flores, R.A., Jungmann, M. and Renter, J., 2022. D4. 3: Digital Twin supported lean project planning, control and risk management.

Johansson, M. and Eklund, P., 2020. A Digital Twin for Risk Modeling and Decision-Support in a Smart Energy Grid. In: *DS 103: Proceedings of the 22nd International DSM Conference (DSM 2020)*, MIT, Cambridge, Massachusetts, October 13th-15th 2020 (pp. 1-9).

Josse, F., 2024. The connection between the" Zero Net Artificialisation 2050" objective and the" Urban Digital Twin" tool, a methodology for assessing strategies to reduce the risk of urban heat islands using data (No. EGU24-17811). *Copernicus Meetings*.

Juarez, M.G., Botti, V.J. and Giret, A.S., 2021. Digital twins: Review and challenges. *Journal of Computing and Information Science in Engineering, 21*(3), p.030802.

Kaewunruen, S., Sresakoolchai, J., Ma, W. and Phil-Ebosie, O. 2021. Digital Twin Aided Vulnerability Assessment and Risk-Based Maintenance Planning of Bridge Infrastructures Exposed to Extreme Conditions. *Sustainability, 13*(4), p.2051. doi:https://doi.org/10.3390/su13042051.

Khan, M.S., Chinnaiyan, R., Balachandar, S., Ibrahim, S.J.A., Chakravarthy, N.K., Kalaiarasan, C. and Divya, R., 2022, December. Centralized and reliable digital twin models for smart city's buildings protection during disaster. In: *2022 International Conference on Computational Modelling, Simulation and Optimization (ICCMSO)*, pp. 226-229. IEEE.

Kim, J., 2023. Digital Twin City for Enhanced Data Mapping and Virtuality-Reality Connectivity: Toward Risk-Informed Decision Making. *Doctoral dissertation*.

Knapen, A. and Holmström, J., 2020, December. A Digital Twin for Safety and Risk Management: A Prototype for a Hydrogen High-Pressure Vessel. In: *Designing for Digital Transformation. Co-Creating Services with Citizens and Industry: 15th International Conference on Design Science Research in Information Systems and Technology, DESRIST 2020*, Kristiansand, Norway, December 2–4, 2020, Proceedings (Vol. 12388, p. 369). Springer Nature.

Koshimura, S., Adriano, B., Mas, E., Nagata, S. and Takeda, Y., 2024. Tsunami Digital Twin–Concept, Progress, and Application to the 2024 Noto Peninsula Earthquake Tsunami Disaster, Japan (No. EGU24-14673). *Copernicus Meetings.*

Kwok, P.K., Yan, M., Qu, T. and Lau, H.Y., 2021. User acceptance of virtual reality technology for practicing digital twin-based crisis management. *International Journal of Computer Integrated Manufacturing, 34*(7-8), pp.874-887.

Lagap, U. and Ghaffarian, S., 2024. Digital post-disaster risk management twinning: A review and improved conceptual framework. *International Journal of Disaster Risk Reduction*, p.104629.

Lifecycle Insights, (2022). *The 2022 Digital Twin Report*. [pdf] Available at: https://blogs.sw.siemens.com/wp-content/uploads/sites/41/2022/05/The-2022-Digital-Twin-Report-by-Lifecycle-Insights.pdf

Liu, C., Wang, Y., Purvis, L. and Potter, A., 2022. The application of Digital twin technology in supply chain resilience and risk management. In: *Symposium on Logistics*, 27 (2), pp. 182-206.

Liu, C., Zhang, C., Wang, B., Tang, Z. and Xie, Z., 2022. Digital twin of highway entrances and exits: A traffic risk identification method. *IEEE Journal of Radio Frequency Identification, 6*, pp.934-937.

Liu, Z., Zhu, M. and Wang, S., 2024. *Safety Behaviour Analysis and Risk Evaluation Method of Human–Construction Robotics and Automation Interaction in Intelligent Construction Scenarios Driven by Deep Learning and Digital Twin*. Available at SSRN No. 4795420.

Mariano, P.O.P., da Silva, F.B.L., Sônego, Y.S.S., Vaz, C.E.V. and Cuperschmid, A.R.M., 2024. A Low-cost Sensor for Slope and Risk Areas Monitoring: Using a Digital Twin for Landslide Prevention. In: *XXVII International Conference of the Ibero-American Society of Digital Graphics (SIGraDi 2023 Accelerated Landscapes)*, São Paulo, Brazil, pp. 1428–1439. Blucher Design Proceedings. doi:10.5151/sigradi2023-91.

Mchirgui, N., Quadar, N., Kraiem, H. and Lakhssassi, A., 2024. *The Applications and Challenges of Digital Twin Technology in Smart Grids: A Comprehensive Review*. Applied Sciences, 14(23), Article 10933. doi:10.3390/app142310933

McKinsey & Company, (2023). *Digital twins: From one twin to the enterprise metaverse*. [online] Available at: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/digital-twins-from-one-twin-to-the-enterprise-metaverse

McKinsey, 2023. *What is digital-twin technology? McKinsey*. [online] www.mckinsey.com. Available at: https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-digital-twin-technology

Microsoft, 2025. *What is Azure Digital Twins?* [online] Available at: https://azure.microsoft.com/en-us/products/digital-twins

O'Neill, S., 2024. *Turning a New Leaf: Digital Twins and AI Are Helping Countries Around the World Prepare for Climate Change, Including Boosting Tree Shade in Argentina*. [online] Available at: https://blog.bentley.com/insights/turning-a-new-leaf-digital-twins-and-ai-are-helping-countries-around-the-world-prepare-for-climate-change-including-boosting-tree-shade-in-argentina/

Priyanka, E.B., Thangavel, S., Gao, X.-Z. and Sivakumar, N.S. 2021. Digital twin for oil pipeline risk estimation using prognostic and machine learning techniques. *Journal of Industrial Information Integration*, [online] p.100272. doi:https://doi.org/10.1016/j.jii.2021.100272.

PTC Inc., 2025. *ThingWorx: Industrial IoT Software | IIoT Platform.* [online] Available at: https://www.ptc.com/en/products/thingworx

Qin, Z., Liang, S. and Liu, Q., 2022. Quantitative Assessment Model of IT Operation and Maintenance Operation Risk Based on the Digital Twin Model. *Scientific Programming*, 2022(1), p.4210927.

Riascos, R., Majićbc, T., Ostrosi, E., Sagot, J.C. and Stjepandić, J., 2023, November. Digital Twin as Enabler of Sustainability and Risk Management of Medical Devices. In: *Leveraging Transdisciplinary Engineering in a Changing and Connected World: Proceedings of the 30th ISTE International Conference on Transdisciplinary Engineering*, Hua Hin Cha Am, Thailand, July 11-14, 2023 (Vol. 41, p. 453). IOS Press.

Riaz, K., McAfee, M. and Gharbia, S.S., 2023. *Management of climate resilience: Exploring the potential of digital twin technology, 3D city modelling, and early warning systems*. Sensors, 23(5), p.2659. Available at: https://pmc.ncbi.nlm.nih.gov/articles/PMC10007107/

Rodrigues, S.S., Braga, J.O., Xavier, J.M., Pauli, G., Mata, A.M., Margotti, E., Demay, M.B. and Donatelli, G.D., 2023, October. Digital Twin of Subsea Assets as a Tool for Integrity Management and Risk-Based Inspection: Challenges and Perspectives. In: *Offshore Technology Conference Brasil,* p. D021S024R005. OTC.

Rosen, R., Von Wichert, G., Lo, G. and Bettenhausen, K.D., 2015. About the importance of autonomy and digital twins for the future of manufacturing. *Ifac-papersonline, 48*(3), pp.567-572

Sadat Mohammadi, M., 2022. Human-Centric Digital Twin Model of Electric System Maintenance Technicians for Near Real-Time Health and Ergonomic Postural Risk Monitoring.

Sander, P., Spiegl, M., Burns, T. and Reilly, J., 2022. Digital project twin for quantitative cost, risk and schedule assessment of capital projects. *Australian Journal of Multi-Disciplinary Engineering, 18*(1), pp.34-46.

Shaharuddin, S., Abdul Maulud, K.N., Syed Abdul Rahman, S.A.F. and Che Ani, A.I., 2022. Digital twin for indoor disaster in smart city: A systematic review. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 46*, pp.315-322.

Shamanna, P., Dharmalingam, M., Vadavi, A., Thajudeen, M., Keshavamurthy, A., Bhonsley, S. and Joshi, S., 2024. Abstract P468: Correlation Among A1c Improvement, Weight Reduction, and Decreased ASCVD Risk in Participants Enrolled for Type 2 Diabetes Remission: Outcomes at 1 Year From an RCCT Using Whole-Body Digital Twin Technology. *Circulation*, 149(Suppl_1), pp.AP468-AP468.

Shamanna, P., Joshi, S., Shah, L., Dharmalingam, M., Vadavi, A., Damodaran, S., Mohammed, J., Mohamed, M., Poon, T., Keshavamurthy, A. and Thajudeen, M., 2022. Correlation of Diabetes remission with reductions in blood pressure and cardiovascular risk scores: results of six months of randomised trial with digital twin technology. *Journal of Hypertension, 40*(Suppl 1), pp.e75-e76.

Shan, S., Song, Y., Wang, C. and Ji, W., 2024. Influencing factors and action paths for public crisis governance performance improvement in digital twin cities. *Library Hi Tech*.

Siemens, 2025. *Digital Twin – Siemens*. [online] Available at: https://www.sw.siemens.com/en-US/technology/digital-twin/

Smart Dublin, n.d. *Smart DCU*. [online] Available at: https://smartdublin.ie/smart-districts/smart-dcu/

Srivastava, G. and Bag, S., 2025. *Harnessing digital twin technology to enhance resilience in humanitarian supply chains: An empirical study*. Benchmarking: An International Journal. Available at: https://www.emerald.com/insight/content/doi/10.1108/BIJ-12-2024-1143/full/html

Sularno, D.P.M. and Astri, R., 2024. Geographic Information System (GIS) of Natural Disasters and Evacuation Routes. *AIP Conference Proceedings, 2891*(1), p.030009.

Sun, Y., Wang, L., Xu, T., Ma, Z. and Wang, X., 2024, February. Research on Intelligent Operation and Maintenance Risk Early Warning Technology of Information System Based on Digital Twin. In: *2024 IEEE 3rd International Conference on Electrical Engineering, Big Data and Algorithms (EEBDA),* pp. 1714-1718. IEEE.

Sun, Z., Li, H., Bao, Y., Meng, X. and Zhang, D. 2023. Intelligent Risk Prognosis and Control of Foundation Pit Excavation Based on Digital Twin. *Buildings*, [online] 13(1), pp.247–247. doi:https://doi.org/10.3390/buildings13010247.

Suquet, R.R., Nguyen, T.H., Ricci, S., Piacentini, A., Bonassies, Q., Sadki, M., Fatras, C., Lavergne, E., Gaudissart, V., Guzzonato, E. and Prugniaux, M., 2024, July. The SCO-Flooddam Digital Twin Project: A Pre-Operational Demonstrator for Flood Detection, Mapping, Prediction and Risk Impact Assessment. In: *IGARSS 2024-2024 IEEE International Geoscience and Remote Sensing Symposium,* pp. 2009-2012. IEEE.

Talukder, A.K., Selg, E. and Haas, R.E., 2022, November. Physicians' Brain Digital Twin: Holistic Clinical & Biomedical Knowledge Graphs for Patient Safety and Value-Based Care to Prevent the Post-pandemic Healthcare Ecosystem Crisis. In: *Iberoamerican Knowledge Graphs and Semantic Web Conference,* pp. 32-46. Cham: Springer International Publishing.

Tan, J.K.N. and Law, A.W.K., 2024. Digital twin of ventilation system against COVID-19 transmission and infection risk. In: *Features, Transmission, Detection, and Case Studies in COVID-19*, pp.163-170.

Tonmoy, F.N., Hasan, S. and Tomlinson, R. 2020. Increasing Coastal Disaster Resilience Using Smart City Frameworks: Current State, Challenges, and Opportunities. *Frontiers in Water, 2*. doi:https://doi.org/10.3389/frwa.2020.00003.

Turner, R. and Sun, Q.C., 2023. Advancing Flood Resilience: A Responsive Digital Twin Framework for Real-Time City-Scale Flood Modelling and Disaster Event Monitoring. Available at SSRN No. 4643740.

TWI Global. (2024). *What is Digital Twin Technology and How Does it Work?* [online] Available at: https://www.twi-global.com/technical-knowledge/faqs/what-is-digital-twin

Wang, Y.Y., Chen, K., Wen, Z. and Jiang, Z.H., 2024. Assessing risk of acute respiratory infectious diseases in crowded indoor settings with digital twin and precision trajectory approach. *Environmental and Sustainability Indicators, 23*, p.100424.

Wolf, K., Dawson, R.J., Mills, J.P., Blythe, P. and Morley, J., 2022. *Towards a digital twin for supporting multi-agency incident management in a smart city*. Scientific Reports, 12, Article number: 16221. Available at: https://www.nature.com/articles/s41598-022-20178-8

Won, S.H., Kim, S.H. and Kim, S.M., 2022. Proposal of the Training System in Disaster Safety with Digital Twin and eXtended Reality Technology. *Journal of Cadastre & Land InformatiX, 52*(2), pp.103-119.

Yang, S. and Lee, K., 2022. Mental Healthcare Digital Twin Technology for Risk Prediction and Management. *The Journal of Bigdata, 7*(1), pp.29-36.

Yu, D. and He, Z. 2022. Digital twin-driven intelligence disaster prevention and mitigation for infrastructure: advances, challenges, and opportunities. *Natural Hazards*. doi:https://doi.org/10.1007/s11069-021-05190-x.

Yu, D.S. and Kim, W.S., 2021. Implementation of UWB Indoor Positioning and Real-time Remote Control System for Disaster Monitoring based on Digital Twin. *Journal of Korea Multimedia Society, 24*(12), pp.1682-1692.

Yuan, R., Zhang, H., Xu, R. and Zhang, L., 2024. Enhancing Coastal Risk Recognition: Assessing UAVs for Monitoring Accuracy and Implementation in a Digital Twin Framework. *Applied Sciences, 14*(7), p.2879.

Zhang, C., Gao, Y., Ye, M., Zhang, M., Wang, B. and Li, Z., 2023, November. A Risk evaluation and control method of highway based on digital twin. In: *2023 IEEE 3rd International Conference on Digital Twins and Parallel Intelligence (DTPI),* pp. 1-5. IEEE.

Zhang, H., Wang, R. and Wang, C., 2019, August. Monitoring and warning for digital twin-driven mountain geological disaster. In: *2019 IEEE International Conference on Mechatronics and Automation (ICMA),* pp. 502-507. IEEE.

Zhihong, T., Shirui, P. and Xianyong, Z., 2020, August. Research on the construction of smart city emergency management system under digital twin technology: Taking the practice of new coronary pneumonia joint prevention and control as an example. In: *2020 4th International Seminar on Education, Management and Social Sciences (ISEMSS 2020),* pp. 146-151. Atlantis Press.

Zio, E. and Miqueles, L. 2024. Digital Twins in safety analysis, risk assessment and emergency management. *Reliability Engineering & System Safety*, p.110040. doi:https://doi.org/10.1016/j.ress.2024.110040.

McMullan, C., & Thakkar, R., 2025, Digital Twins for Impact (DT4I): Using Digital Twins to Deliver Effective Risk and Emergency Management, Dublin: Dublin City University

DCU BUSINESS SCHOOL

ISBN 978-1-919358-44-4