Digital Twinning for Crisis Response in Transport-based Scenarios: Establishing the Opportunities, Challenges, Vulnerabilities, and Risks

DTBOC – Digital Twins Beyond Observed Capabilities

Literature Review

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October 2024

RBOC Network

DTNet+

Acknowledgment

DTBOC (Digital Twinning Beyond Observed Capabilities) is a collaboration between the Digital Twinning Network + (DTNet+) and Resilience Beyond Observed Capabilities Network + (RBOC N+). DTBOC is funded by the UK Department for Transport (DfT) via the Engineering and Physical Sciences Research Council (EPSRC). The authors gratefully acknowledge this support.

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Abbreviations

AI	Artificial Intelligence
AIS	Automatic Identification System
AR	Augmented Reality
BIM	Building Information Management
CCI	Critical Cyber Infrastructure
CDT	Cognitive Digital Twin
CORE	COllaborative REsponse
CPS	Cyber-Physical System
CSBS	City Sensing Base Station
DT	Digital Twin
EMS	Emergency Medical Services
EWS	Early Warning System
FICUS	Framework Integrating the Complexity of Uncertain Systems
GDPR	General Data Protection Regulations
GIS	Geographic Information System
GSR	Ground Surveillance Robot
iDT	Intelligent Digital Twin
IFC	Industry Foundation Classes
IoT	Internet of Things
JESIP	Joint Emergency Services Interoperability Principles
LiDAR	Light Detection and Ranging
MAS	Multi-Agent Systems
ML	Machine Learning
PEIMAF	Internal Emergency Plan in case of Massive Influx of Patients [Italian]
PT	Physical Twin
RFID	Radio-Frequency Identification
SAR	Synthetic Aperture Radar
SC	Supply Chain

SCDT	Smart City Digital Twin
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UDT	Urban Digital Twin
VM	Virtual Machine
VR	Virtual Reality
WRCH	Water-Related Climatic Hazards

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Executive Summary

This review focuses on the literature surrounding digital twins for crisis response and resilience. In total, 56 articles were gathered, reviewed, summarised, compiled and analysed based on their relevance to the DTBOC project.

We found significant progress in the literature in recent years, particularly in the context of smart cities. However, the scope of digital twins extends far beyond urban management. Applications include training first responders in simulated crisis scenarios; enhancing data availability and sharing among response stakeholders; providing real-time situational awareness to decision-makers; and enabling more efficient resource allocation during emergencies.

Digital twins are a flexible tool, and research is being conducted into their use in numerous, diverse areas. In terms of crisis response and resilience, the bulk of the research focuses on the use of digital twins in either the preparedness or response stages of disaster response. There is significantly less research on the use of digital twins in the recovery phase. There is also a healthy body of research on the topic of resilience of the digital twins themselves.

While digital twins have the potential to significantly improve resilience to crises, as the field evolves, it will be crucial to address challenges related to data integration, security, privacy, and social acceptance. Future research should focus on these aspects while continuing to explore new applications and refine existing ones.

While there is considerable potential for DTs in this field, there are also considerable technical, social, and scientific challenges. DTs are digital systems that rely on data flows. Therefore, cyber security, data sharing, and interoperability are all significant, but not insurmountable challenges. There is also a lack of research into the efficacy of DTs – that is, studies that scientifically quantify results of where DTs are used compared with a control where DTs are not applied.

Digital twins hold considerable potential and can work well when applied to these kinds of challenges. However, the Technology Readiness Level of crisis response digital twins is currently estimated at around levels 4-5, lower than digital twins in some other areas. Significant further work and investment is required to achieve the full potential offered by digital twins for crisis response and resilience.

1. Introduction

DTBOC (Digital Twinning Beyond Observed Capabilities) is a collaboration between the Digital Twinning Network + (DTNet+) and Resilience Beyond Observed Capabilities Network + (RBOC N+). DTBOC is funded by the UK Department for Transport (DfT) via the Engineering and Physical Sciences Research Council (EPSRC). It will focus on developing advanced societal resilience using digital twins (DT), guided by the DfT stated aim that "by 2030, to establish a coherent Digital Twin programme across the DfT family and relevant Government Departments to demonstrate leadership and provide a step change in the capabilities throughout the prepare, respond and recover circle, for specific risks."

The DTBOC project will focus on developing a resilience-based framework for digital twinning in transport-based scenarios incorporating single- and multi-hazard threats such as: terrorism, cyber threats, energy and supply chain disruption, accidents and systems failures, natural, environmental and societal hazards, conflict and pandemic. The aim is to deliver a step change in the UK digital twinning capability to better prepare, respond, and recover from the scenarios identified in the National Risk Register (e.g. those listed above) that relate to transport-based scenarios.

The collaboration will focus on four central research questions:

1. What role can digital twins play in crisis preparedness, response, and recovery? And for whom?
2. What are the potential opportunities, threats, vulnerabilities, impacts, and risks associated with the use of digital twins within crisis management?
3. What could a risk-management framework look like for digital twins and crisis management?
4. How can we scale digital twins, enhance speed of response, and establish effective methods for interoperability?

The three-step framework of preparedness, response, and recovery will be used to develop the digital twin concepts for all four of the socio-technical research questions.

The overall aim is to progress towards proof-of-concept crisis and resilience digital twins through a series of two sandpit events leading to the funding of 3-5 projects.

This document provides a general background to digital twins, noting the diverse areas in which DT research has progressed, and a critical academic literature review of current advances and approaches to DTs. The structure is as follows:

- Section 1 provides an overall introduction to the DTBOC project
- Section 2 describes the background of DTs and related terminology
- Section 3 discusses resilience frameworks used by the UK government and its departments

- Section 4 provides an overview analysis of the literature as it relates to the four research questions outlined above
- Section 5 concludes the report
- Appendix A contains succinct, one-paragraph summaries of each of the articles reviewed, organised under the two main headings of ‘DTs for Resilience’ and ‘Resilience of DTs’
- Appendix B presents some numerical analysis of the articles reviewed

2. Digital Twins Background and Terminology

Digital twins (DTs) are virtual representations of physical objects or systems. They leverage data, simulations, and AI methods (like Machine Learning (ML)) to mirror and predict the behaviour of their real-world counterparts (also known as "Physical Twins" (PT)). DTs are designed to continuously evolve, and update based on right-time data inputs, enabling organizations to monitor, analyse, and optimise the performance of their assets throughout their lifecycle. Wagg, et al. (2020) define a DT as "as a virtual duplicate of a system built from a fusion of models and data" (p.3).

The origins of the concept are often traced back to the NASA Apollo space program simulators, used during missions to go beyond mere simulations (e.g Apollo 13) to "rapidly adapt and modify the simulations, to match conditions on the real-life crippled spacecraft so that they could research, reject, and perfect the strategies required to bring the astronauts home" (Ferguson, 2020). To reduce the time and cost of constructing physical twins, Grieves proposed the concept of digital twins in 2011 as a virtual digital representation of a physical product (M. Grieves, 2011). In 2023 Grieves noted "it is a concept that was first adopted for tangible industrial products and has since expanded to all manner of products and services" (2023).

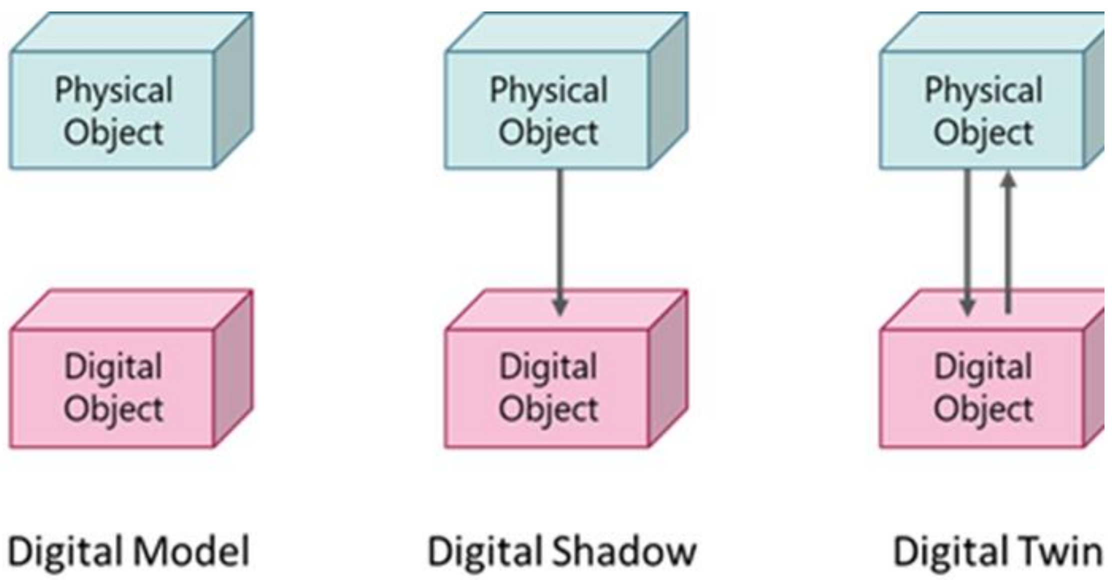

Figure 1: Relative data links between digital models, digital shadows, and digital twins. Source: (Johnston 2023).

An important element of a DT is the *bidirectional* information flow between the physical and digital twins (Kritzinger et al., 2018). This allows the DT to evolve and interact with the PT. Von Lukas notes, "this loop of effecting the real world by making decisions with support of the virtual/digital world is an important characteristic and differentiates the digital twin from a simple model or a digital shadow" (p. 47). It is also worth noting that the "physical twin" does not need to be monolithic: DTs can customise (timing, context) outputs to different recipients, for example to the public, emergency services or other authorities.

Wagg et al. (2020) posit five levels of DTs 1. Supervisory 2. Operational 3. Simulation 4. Intelligent 5. Autonomous. Levels 1 and 2 are categorised as "pre-digital twins" as they lack the essential elements of simulation; learning and management.

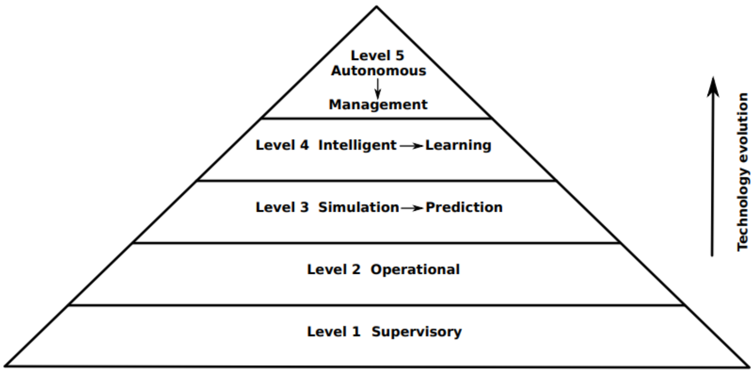

Figure 2: A capabilities hierarchy for digital twins, where each level incorporates all the previous capabilities of levels below. Source: Wagg et al. (2023)

While DTs are a recent innovation there is immense interest and ongoing research into their potential benefits in a wide range of applications. Areas of application range from discrete manufactured products or objects, such as aircraft or bridges, to complex systems of systems such as hospitals, a network of roads and traffic controls, or entire cities.

The concepts of federation and modularity are critical. Federation refers to a network of interconnected but independent digital twins that collaborate and share data to represent a larger system or ecosystem. Modularity refers to the design principle where the digital twin is constructed from discrete, interchangeable components or modules. In the context of a smart city for example, individual DTs could be used for transportation, energy management, and water management, each operating independently but able to share information through standard data protocols. Both federation and modularity enable flexibility, robustness (by being able to replace a module or component without disrupting the whole), scalability through insertion of extra modules or DTs, collaboration, and maintenance.

Many articles express considerable optimism about the potential technological solutions provided by DTs (in combination with related technologies, such as AI/ML, IoT, big data) to address serious challenges such as traffic congestion, supply chain and energy disruptions, transport safety, efficient health systems and critical infrastructure, environmental and sustainability outcomes, and others. However, it is necessary to acknowledge, as many articles do, the many challenges. For example, taking account of the societal impacts and social reactions to new technology that may be viewed as intrusive or controlling by some sections of the community. Protests against the ‘15-minute city’ as a conspiracy to limit mobility and freedoms is one example (Silva, 2023). Stevens (2024) examines “organised opposition to increasing state surveillance powers in the UK”. Similarly, Allam et al. (2022) warn of the potential Orwellian dystopian outcomes if privacy and security concerns are not adequately addressed.

3. The UK Resilience Framework

Specific governmental frameworks apply to the fields of crisis response and resilience. *The Orange Book Management of Risk Principles – Principles and Concepts* (UK Government, 2023a) applies "to all government departments and arm's length public bodies" and sets out the principles for risk management in government. At the local level, the National Resilience Standards for Local Resilience Forums (LRFs) and duties of local government are set out in the Civil Contingencies Act (CCA). The CCA sets obligations for local government under the 'Prepare, Respond and Recover' framework which covers emergency planning, risk assessment, communications, training, exercises, strategic coordination, recovery, and pandemic and cyber preparedness.

Crisis Communication: A behavioural approach (GCS Behavioural Science Team and Cabinet Office, 2022) defines crisis as: "an inherently abnormal, unstable and complex situation that represents a threat to the strategic objectives, reputation or existence of an organisation". It notes that, despite Hollywood depictions, true panic is rarely observed in crises, rather "people often display a strong desire to help others". In anticipating public responses, a "fundamental driver of behaviour" is meeting essential needs. Anticipating needs in a particular crisis will enable "crisis management and communications during or in anticipation of a given crisis" (p.10). As the below studies show, DTs may be particularly useful in modelling and anticipating needs during abnormal circumstances and hence enable the key elements of trust in government, that is; competence, integrity and benevolence.

Prepare. Respond. Recover. Crisis Communications Operating Model (UK Government, 2023b) sets out the framework of Prepare Respond Recover in the context of the UK Central Government Response Concept of Operations (Cabinet Office, 2013).

The three main phases of emergency management are:

- preparation (pre-planning and building resilience);
- response (management or mitigation of an immediate risk or stopping things getting worse);
- recovery (the activity of rebuilding, restoring and rehabilitating structures).

As set out in Figure 3, Emergencies are divided into three levels (significant, serious, catastrophic), as well as the three stages of Prepare, Respond and Recover. It can be noted that COBR (Cabinet Office Briefing Rooms; the Civil Contingencies Committee convened during a national emergency) will likely be convened in response to serious and catastrophic emergencies. Specific government departments – known as Lead Government Departments (LGDs) - are delegated responsibility for certain risks in areas relating to their expertise. Guidance and Best Practice for these LGDs, and a breakdown the risks delegated to each can be found in *The Lead Government Department and its role – Guidance and Best Practice* (Cabinet Office 2004).

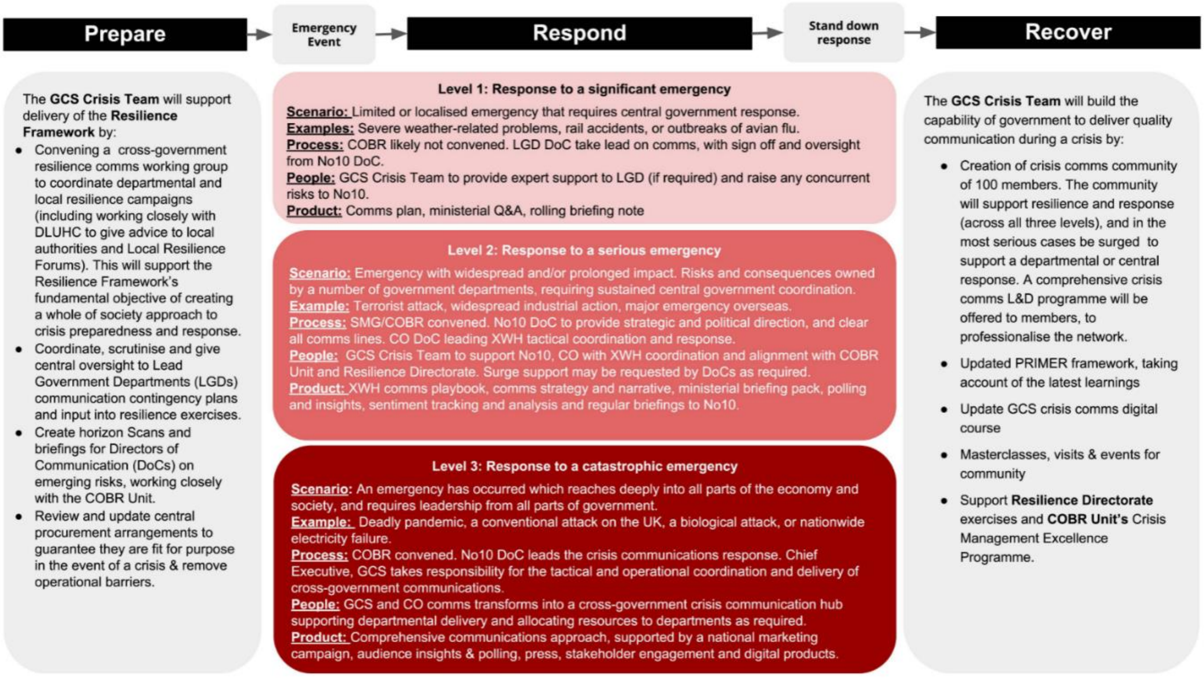

Figure 3: Government Communications Service framework for crisis response under the three stages of Prepare, Respond and Recover, as well as the three levels of severity (significant, serious and catastrophic). Source: (Cabinet Office, 2013).

Resilience is defined by the UK Government Resilience Framework (2022) (UK Government, 2022a) as "The UK's ability to anticipate, assess, prevent, mitigate, respond to, and recover from natural hazards, deliberate attacks, geopolitical instability, disease outbreaks, and other disruptive events, civil emergencies or threats to our way of life" (p.76). In other words, the ability to withstand or quickly recover from a difficult situation, and to 'get ahead' of those risks and tackle challenges before they manifest. The framework highlights that true resilience is a 'whole of society' endeavour. The ability of multiple stakeholders, such as response agencies and government departments, to achieve collaborate and share critical data in an emergency context is key to disaster response. Relevant frameworks exist in both areas in the forms of the Joint Emergency Service Interoperability Programme (JESIP), the Data Sharing Governance Framework (UK Government, 2022b), the National Decision Model (College of Policing, 2013) (specific for police), and the Joint Decision Model (JESIP, 2024). These frameworks provide high level guidance for governmental response and cooperation in emergencies. However individual agencies still bear the responsibility of making critical decisions based on the context of the specific emergency, the relevant regulatory powers and limitations that apply, and the varying ethical priorities in play.

4. Digital Twins For Crisis Response and Resilience

Digital twins represent a rapidly evolving field with applications spanning diverse domains, from their roots in space exploration, engineering and manufacturing to broader uses in urban planning, healthcare, and crisis management.

The complexity of DTs, which often involve multiple functionalities, data types, and devices, presents significant challenges for seamless integration and reliability. Security considerations, including the principle of "security by design," are crucial but often overlooked in current research. Moreover, the social and cultural implications of DTs, particularly concerns about surveillance and monitoring, warrant careful consideration.

Literature Review Methodology

This literature review is intended to provide participants in the DTBOC project a representative snapshot of the kinds of research into DTs that has taken place in recent years (i.e. post-2020). It is not exhaustive of DT research but aims to achieve a cross section of domain areas, types of technological approaches, and countries/regions. The review focuses on the academic literature only and does not consider articles or press releases without peer-review. This approach necessarily misses technologies with a higher readiness level being produced in the private sector but does avoid the difficulty of assessing the accuracy of unverifiable claims in marketing materials.

Hence, multiple searches were conducted on the *Locate* online library resource using the search term “Digital Twins resilience”. Articles were then filtered to exclude those prior to 2020, and those not relevant to crisis response or resilience. Follow up searches were then conducted using *starPlus* library search using the terms listed in Table 4, with the aim of finding articles covering topics with poor coverage from the initial search. From those that remained 54 articles were selected based on a reading of their abstracts and relevance to the project (two relevant articles published during the project were added at the conclusion of writing up the literature review to make a total of 56).

Those articles are classified according to the stages of resilience i.e. Preparedness, Response or Recovery, that they most applied to. Within those categories, the articles have been grouped according to the domain they apply to, for example, "Emergency Services/First Responders”. This is purely for the readers’ convenience and does not indicate any further linkage between the methodologies or authors of the articles. Some articles clearly apply to both Preparedness and Response, and this has been indicated in the key words for each article. Some numerical analysis of the domains, stages of resilience and country are presented in graphs. The articles summaries were used as the basis of an analysis presented in the following section, and the summaries themselves are presented in full in Appendix A.

Library	Search term
Locate	Digital Twins resilience
StarPlus	Disaster recovery review technology Digital twin(s) crisis recovery Digital twin(s) emergency recovery Effectiveness digital twins resilience Effectiveness digital twins crisis response Transport digital twin review Transport disaster response Effectiveness digital technologies decision making

Figure 4: Literature review search terms

Analysis

In this section, we describe some of the common themes found across the literature, including both the potential benefits of, and challenges to, digital twins for crisis response. A more detailed review of all articles analysed, categorised by disaster response phase and disaster type, can be found in Appendix A.

A numerical analysis of the literature is presented in Appendix B. Of the articles cited in this review, the majority (34) cover the preparation phase of crisis response, followed by response with 19 articles and one for recovery. Geographical regions with the highest research outputs from this sample are the EU (21), followed by China (13), US (8) and UK (6).

Potential Benefits

In the *preparedness* phase, DTs have the potential to play a significant role in enhancing readiness for potential crises. They allow for the simulation of various scenarios, testing of different response options, and identification of vulnerabilities and optimal response plans before an actual crisis occurs. This capability is particularly valuable for emergency responders, government agencies, and critical infrastructure operators. Kajba et al. (2023) note the most frequently researched areas for DTs are logistics, transportation, and supply chains. Allam et al. (2022) note the "vast troves" of data combined with 5G and 6G networks that will bring to life the full prospects of automation and intelligence. Chen et al. (2023) describe how a fusion of data from multiple sources including emission levels, soil moisture, pH, airborne toxins, and traffic speed monitoring can provide an overall picture to inform traffic and flood responses.

Urban planners and city managers can use DTs to design more *resilient cities* and improve emergency response capabilities. Allam et al. (2022) link smart cities with the "15-minute city" concept, noting the potential of DTs to transform urban areas to be more liveable and resilient. Gkontzis, Kotsiantis, Feretzakis, and Verykios (2024), meanwhile, present a prototype citizen-feedback Smart City DT for the city of Patras, based on five years of historical data. The authors claim that, using machine learning, predictions can be made up to six months ahead regarding the type of issue, probability and location of issues. The authors note the absence of standardised protocols for seamless data sharing across systems and platforms.

DTs can also provide immersive virtual environments for *training* first responders and decision-makers, allowing them to practice and refine their skills in a safe, controlled setting. Smit, Voûte, & Verbree, (2021) created first responder simulations using Head-mounted Displays (HMDs), HoloLens, and the Mixed Reality Toolkit to create 3D maps. Kwok et al. (2021) demonstrate combining virtual reality and DTs for emergency response training in chemical plants, highlighting the importance of realistic simulations, and noting that user-friendliness will be of key importance in the adoption of this technology by end-users, therefore sufficient training to become familiar with the tech is essential prior to real-world deployment.

Resource allocation and *supply chain resilience* are critical factors in crisis preparedness. For example, Ribeiro, Gonçalves, & Bartolomeu, (2023) created a DT of Portugal's entire ambulance fleet allowing the matching of ambulance and personnel types to particular emergency requirements, as well as automated route planning and transfer of patients with specific needs. Bentley (2023), meanwhile, describes how using a DT to predict crime hotspots and deploy mobile licence plate readers accordingly led to reductions in actual crime rates. Ivanov & Dolgui (2021) use a DT to simulate the impact of pandemic on food supply chains across several countries in Europe from a limited number of distribution centres.

Multiple studies examine DTs in the context of *pandemic* and *supply chain resilience*, including Lu et al. (2021), Lv, Qiao, Mardani and Lv (2022) and Pang, Huang, Xie, Li, and Cai (2021). Girotto et al. (2024) focus on the link between water-related climatic hazards and outbreaks of life-threatening diseases, emphasizing the potential of DTs in enhancing disease outbreak prediction. Rodríguez-Aguilar and Marmolejo-Saucedo (2020) propose a conceptual model for integrating digital twins with multi-paradigm modelling for planning the management of health services in public health emergencies.

During the *response* phase, DTs can provide real-time situational awareness by integrating multiple data streams from various sources, giving crisis managers a comprehensive view of the unfolding situation. Adegoke (2023) discusses the prevalence of using big social media data, particularly Twitter, as a tool in all stages of preparedness, response and recovery, but cautions against over-reliance on generalisations based on social media.

DTs can also optimize resource deployment and facilitate coordination between different agencies, a crucial factor in effective crisis response. Wolf et al. (2022) demonstrate this with their prototype for multi-agency incident management in a smart city context. The twin identifies the closest responders and allocates them to the incident, while keeping all emergency response stakeholders informed in real-time.

Many other articles discuss the potential benefits in the field of smart cities. One common topic is the *optimisation of road traffic* for safety and to aid emergency vehicle routing, as described by Feng, Lv & Lv (2023), Deren, Wenbo and Zhenfeng (2021), Li et al (2024) and Faliagka et al. (2024). Zhaohui Wu, Chang, Li, and Cai (2022) discuss the difficulties of monitoring and maintenance of traffic flow in tunnels and present a DT for enhanced response to a traffic incident in a tunnel using BIM, IoT data and real-time "video fusion into 3D virtual scene". A similar technology is applied to water traffic by (Z. Wu et al., 2021). Li et al. simulate the impacts of flooding on the urban road networks of Shanghai, allowing policy makers to identify roads that are susceptible to congestion in a crisis and take corrective actions accordingly.

DTs can be used to guide *evacuation efforts* and emergency response activities, potentially saving lives and minimizing damage. Park et al. (2018) and Wong and Lee (2023) both examine combining multiple data sources for emergency response in high-rise buildings enabling responders to locate victims, exits and optimal pathways in low-vision scenarios.

Resource allocation is at least as important in the response phase as in the preparedness phase. Rodríguez-Aguilar and Marmolejo-Saucedo (2020) examine hospitals in crisis response scenarios and advocate using smart sensors to collect real-time information enabling optimisation of resource allocation including drugs, equipment, and human resources.

Less research could be identified in this review for the use of DTs in the *recovery* phase. Ghahari et al. (2022) present a novel model for bridge digital twinning that can be used for rapid post-earthquake damage assessment and decision-making for infrastructure rehabilitation. There is much potential for future studies in this area.

Challenges

The implementation of DTs in crisis management is not without challenges and risks. While they offer significant opportunities, they can also introduce new vulnerabilities.

Cybersecurity risks are a major concern, as the increased connectivity and critical nature of DT systems create an expanded attack surface for malicious actors. Alcaraz and Lopez (2022) explore these security threats and propose various security approaches for DTs. *Privacy concerns* also arise from the data collection and integration required for effective DTs. Holmes et al. (2021) recognize these risks but also highlight the opportunities for DTs themselves to mitigate cybersecurity risks and become an integral part of a security-in-depth defence. Several authors have explored the potential of digital twins (DTs) to enhance cybersecurity. Salvi et al. (2022) propose using DTs to build resilience in critical cyber infrastructure (CCI), such as energy and transportation systems, enabling simulations, training, and information sharing among stakeholders.

To address these challenges and mitigate risks, a comprehensive risk management framework for DTs in crisis management is essential. This framework should encompass robust cybersecurity measures, including regular audits and resilience testing. Clear data governance policies are crucial, covering all aspects of data collection, usage, sharing, and privacy protection. Rigorous validation of DT models and simulations is necessary to ensure their accuracy and reliability – Wagg et.al (2020) note the need to quantify uncertainty in DTs. Fogli et al. (2024) examine how "chaos engineering" can be applied to improve the resilience of DTs, providing insights into potential risk management strategies. Multiple articles discuss the resilience and cybersecurity of DTs themselves, see: (Fogli et al. 2024), (Alcarez & Lopez, 2022), (Holmes et al. 2021) and (Jin et al. 2022).

Scaling DTs and enhancing their speed of response presents both technical and organizational challenges. From a technical standpoint, leveraging cloud computing and edge technologies can provide the increased processing power and reduced latency needed for real-time operations. Jang and Jung (2023) propose a novel technology based on "subminiature low-power IoT technology" combined with signal processing algorithms for enhanced flood monitoring, demonstrating how advanced technologies can improve the speed and accuracy of crisis response systems. Federation and modularisation of DTs are of key importance to the challenges of scaling up flexible, robust, DT solutions.

Also of key importance is an appreciation of the *human factors* involved in implementing DTs; that is, how they are designed, used and adopted for and by end-users, and factors involved with reluctance to cooperate and share data between relevant stakeholders and agencies. Wolf et al. (2022) emphasise a systems engineering approach to designing technology with the end-user in mind and allowing their input in the design where possible. Kwok et al. (2021) stress the critical importance of user-friendliness and extensive training prior to real-world deployment for effective adoption by end-users. Gutiérrez et al. (2023) highlight the issue of cognitive load of first responders and the need to avoid overloading the responders with too much information in complex, critical situations. Allam et al. (2022) note the importance of consulting residents of smart cities, allowing them to visualise, interact with, and incorporate their expectations into the models and outcomes, to increase community *ownership* and acceptance.

Interoperability is a key challenge in the implementation of DTs for crisis management, given the multiple agencies and systems typically involved in crisis response. Wagg et al. (2020) discuss the organizational challenges of the "silo effect" (p.3) which can prevent unification of models and lead to "analysis paralysis". Developing common data standards and exchange formats is crucial to ensure different systems can communicate effectively. Pang et al. (2021) note the tension between *data privacy concerns* which can lead to data silos, and the need to share data for deep learning to occur across data sources – therefore they propose a federated learning paradigm. To address the interoperability challenge of DTs, Lehmann et al. (2023) discuss the concept of a "Marketplace of Intelligent Digital Twins" and emphasize the importance of Multi-Agent Systems (MAS) in enabling intelligent interaction and collaboration between digital twins. Ye et al. (2023) note that that cloud-based systems with distributed data management can facilitate fusion.

We note a decided lack of evidence-based research around the *efficacy* of digital twins, in terms of aiding decision making in crisis response situations. While this is understandable, given the nascency of the field and the difficulties in quantifying decision making, it nevertheless presents a gap in the literature and an opportunity for future research.

5. Conclusion

Digital twins offer significant potential to enhance crisis management across all phases, from preparedness through response to recovery. They promise to provide crisis managers with unprecedented situational awareness, predictive capabilities, and decision support tools. However, realizing these benefits requires careful management of associated risks and challenges, particularly in the areas of cybersecurity, privacy, and system integration. A comprehensive approach addressing technical, organizational, and human factors will be crucial for successfully implementing digital twins in crisis management. As this technology continues to evolve, it has the potential to significantly improve our ability to prepare for, respond to, and recover from crises, ultimately saving lives and minimizing damage in emergency situations.

This literature review, while not exhaustive, provides a representative sample of DT research across various sectors and geographical regions. It offers insight into the current state and potential future directions of DT technology in crisis preparation, response, and recovery.

As we move forward, the integration of DTs with other emerging technologies such as artificial intelligence, machine learning, and the Internet of Things promises to further enhance our crisis management capabilities. Continued interdisciplinary collaboration will be essential to fully realize the potential of digital twins in creating more resilient and responsive systems across various sectors of society.

Appendix A: Categorised Summaries of Articles

Digital Twins Overview

Wagg et al. (2020) present the application of DTs to engineering dynamics problems including a literature review and background of DTs. They note DTs are a recent and potentially transformative idea that applies to both design and asset management phases of physical twins (PTs). The article stresses the predictive benefits of DTs that are time evolving and updating in near-real time using machine learning for improved user decision making. The article also defines five levels of sophistication of DTs from levels 1 and 2 Supervisory and Operational (defined as pre-DTs) to Level 3 Simulation, Level 4 Intelligent and Level 5 Autonomous. The article also notes, however, the *uncertainty* in DTs and the need to quantify uncertainty and technical challenges and research questions, in particular connectivity and integration between different silos of design and data, coordinating multiple tasks, and ensuring robust workflows. It presents case studies of a wind turbine and a simple three-storey structure DT that "demonstrates that by moving up the levels of a digital twin more information and improved decision making can be made" (p.21).

Lehmann et al. (2023) discuss DT paradigms for enhancing resilience in areas outside of manufacturing. The article talks about a socio-technical revolution with the arrival of "Industry 5.0" and cites the EU White Paper on Industry 5.0 emphasising social values of being "human centric, sustainable, resilient" (p.1). Therefore, "DTs must develop active, online, goal-seeking, and anticipatory characteristics to achieve their full potential" (p.4). It also emphasises the important role of Multi-Agent Systems (MAS); autonomous agents capable of interacting, cooperating, coordinating and negotiating with each other as humans do. It presents a use case of a "Marketplace of Intelligent Digital Twins … a microservice-based and dynamically event-driven framework" (p.16), noting "it is through the use of MAS paradigms that DTs can become intelligent" (p.19). While the use case in the article presents a marketplace for maximising manufacturing efficiencies through an internet of digital twins "a green field for the all-encompassing interaction and collaboration of iDTs" p.20) the authors note it can be applied in "every other domain" (p.20).

Ye et al. (2023) present Urban Digital Twins (UDTs) for community infrastructure resilience. The article from Texas A&M touches on many of the themes of the DTBOC project, that is, using UDTs for human-centred community resilience. It notes multiple international studies from Ireland, Singapore, and Germany, for applications including smart traffic management, public epidemic control, and smart flood monitoring. The article notes several challenges including that most UDTs are customised ad hoc systems and that there is "a lack of flexible UDT platforms to integrate multiple datasets from different sources" (p.192). Also, that cloud-based systems with distributed data management can facilitate fusion. The study suggests that "future

UDT for coastal infrastructure resilience needs to integrate multi-sourced data analytics, human-centred infrastructure risk assessment, 3D urban visualization, and AI into the same framework" (p.195). Ultimately, the UDT model presents potential for a "multisensory learning environment for collective planning and evidence-based decision making" (p.195).

Kajba et al. (2023) conducted a literature review on digital twins in the transport and energy fields. They found the most frequently studied fields to be logistics (24 papers out of 55), transport (21 papers) and supply chains (19). In terms of modality, road transport was the most studied (15/55), followed by urban (8) and maritime transport (8). Smart cities (20/55) were the most common environment to be studied. The authors noted a lack of research on practical implementations or in real environments.

Effectiveness of Digital Twins

Digital twins were identified as a 'hyped' technology by Bosch-Sijtsema et al., alongside 10 other technologies. Here, hype is defined by the ratio between how widespread knowledge of a particular technology is and how widespread its usage is. The authors refer to the Gartner hype curve and categorise technologies into four zones: 'Confusion', 'Excitement', 'Experimentation', and 'Integration'. In this study DTs fell into the Experimentation category with 40% of respondents expecting to use DTs within 5 years and 10% expecting to never make use of DTs. This can be contrasted with BIM – the least hyped technology investigated- (60% >5 years, 10% never) and self-driving vehicles – the most hyped – (10% <5 years, 20% never). It should be noted that this study was limited to the Swedish architecture, engineering and construction sector, which is lagging traditional predictions made by the Gartner curve.

Related Projects and Topics

Adegoke (2023) conducted a systematic literature review on the use of big (social media) data in natural disasters. They typified research into five categories: crisis decision making, crisis communication, disaster preparedness, disaster recovery, and social media as a public space. They identified gaps in disaster preparedness and mitigation and noted the dominance of Twitter as a tool in all categories. Caution is recommended in not over-relying on generalised conclusions from social network analysis and that that trust relationships have a tangible impact on efficacy.

A cluster of Horizon2020 research projects exist which, while not directly relating to digital twins, do impact related technologies in the field of disaster response. These include RESCUER (Jorge 2022), which focuses on a technology-based toolkit for first responders, including augmented reality, biometric sensing, and communication, command and control infrastructure; ASSISTANCE (Robles et al. 2020), a situational awareness platform for first responders; Med1stMR (Zechner et al.), a next-gen training technology for medical first responders using virtual reality; FASTER (Katsadouros et al.), a digital ecosystem for first responders incorporating augmented reality, wearable technology and autonomous vehicles; and CURSOR (Ristmae et al. 2021), a technology tool kit for urban search and rescue.

DTs for Resilience: Preparedness

Smart Cities

Allam, Bibri, Jones, Chabaud, and Moreno (2022) link smart cities with the "15-minute city" concept noting the generation of vast troves of data from IoT and the potential to transform urban areas to be more liveable, human friendly, reduce traffic, emissions, energy use, waste, increase mobility, parking, planning, health and cultural vibrancy – based on the four elements of 15-minute cities; density, proximity, digitalisation, and diversity. The article is predominantly optimistic about prospects for "a city to move to a data-driven form of urbanism by leveraging advanced data and information technologies to entirely transform its processes and practices" (p.5), as well as "technology that pervades the fabric of the city" and "requires a much stronger function of intelligence" (p.5). The authors note the importance of DTs to "virtualise, analyse, simulate, test, and map different aspects and scenarios" useful to allow residents to incorporate their expectations, visualise and interact, and increase community *ownership* of the models and outcomes. It notes 5G and coming 6G technology which will "bring to life prospects of full intelligence and automations of systems" (p.12). The article also notes the serious privacy and security concerns and the potential for "Orwellian" dystopian outcomes if those are not adequately addressed.

Chen, et al. (2023) propose what appears to be a true digital twin for sensing and monitoring of a smart city, enabling real-time processing from sensors, cooperative observation, and instant services capable of automated responses including deployment of camera-equipped Unmanned Aerial Vehicles (UAVs) and Ground Surveillance Robots (GSRs). The authors "propose the architecture and prototype devices of the City Sensing Base Station (CSBS). The CSBS architecture includes characteristics like plug-and-play, collaborative observation, supported web services, and open capability for multi-protocol heterogeneous observation platforms" (p.19). The article presents the CSBS as an integrated, plug-and-play, multi-protocol, high resolution, accuracy and immediacy solution for sensing of future cities. It presents two case studies of a burst underground water pipe, and a traffic collision, to show how in-situ sensors deployed at ground level, and attached to streetlights, are able to detect anomalies in soil moisture levels, pH levels, air-borne gases/toxins (SOx, NOx that increase in the event of a traffic collision), speed of traffic flow (e.g. vehicles that are stationary for more than 60 seconds indicating a collision), and able to deploy UAVs and GSRs for further monitoring and analysis of the incident. The system architecture employs multiple communication layers and edge data processing to achieve low latency and rapid data transmission and compute. The prototype system was tested in Wuhan, China with apparently positive results. The social dimension of such a "pervasive" surveillance and monitoring system with elements of "autonomous" responses are not discussed. Nor are the security vulnerabilities of such a manifold, heterogeneous cyber-physical infrastructure discussed. The article may be categorised as one that is highly optimistic and ambitious about high level DTs with automation and autonomy built in.

Faliagka et al. (2024) demonstrate how digital twins can optimize traffic flow, mitigate environmental impact, and enhance emergency response through use cases such as "Smart Parking", "Environmental Behavior Analysis on Traffic Incidents", and "Emergency Management". These use cases are tested on a small scale, before deciding on implementation at a larger and more expensive scale. The authors describe an Open Digital Twin Framework capable of evolving a smart city into a 'Metacity' and point to the giant leap forward in 2018 with the "Smart City Digital Twin" for optimising resilience, sustainability and liveability. AI/ML "supercharge" data analysis uncovering hidden patterns and trends for better decision making. The paper presents the METACITIES initiative which seeks to provide a novel solution for smart mobility using DTs in the three areas mentioned above. The article emphasises the many potential benefits of this approach in terms of reducing traffic congestion, directing users to the most efficient routes and areas with available parking, optimising emergency responses to traffic accidents through redirecting traffic and providing EMS with the optimal routes. The article emphasises "city engagement and participation", fostering "transparency and collaboration between citizens and city authorities" and considers three use case studies, Los Angeles, Barcelona and Singapore concluding that positive results were obtained in all three for optimising mobility outcomes. Also presents the concept of the 'Open Digital Twin Framework', a reference architecture for developers. The challenges of data privacy, accuracy and reliability of AI and ML, high costs, communications, and the digital divide are mentioned, however, the overall tone of the article tends towards hype/endorsement and emphasis on the many potential benefits of reducing traffic fatalities, optimising mobility, sustainability, planning, predictive analysis, analysing "what-if" scenarios, testing policies before implementation, maximising commercial benefits for example from suggesting parking strategies. Monitoring of parking infringements for example, double parking, violation of maximum time allowed and restricted parking areas indicate a level of surveillance that some sectors of community would find intrusive.

Feng, Lv, & Lv (2023) discusses DTs and complex transportation network systems, presenting a literature review. The article examines the adaptability of traffic systems to disturbances and the application of DTs to create an internet of vehicles' that optimises large road traffic systems and reduces traffic congestion.

Deren, Wenbo, & Zhenfeng (2021) discuss smart cities based on "massive urban big data" touching on several relevant themes such as DTs for traffic monitoring using data from mobile phones, surveillance cameras, cameras on taxis, trains and buses, able to analyse levels of congestion and contribute to managing "major event security". The authors discuss epidemic monitoring and response, using spatiotemporal data from mobile phones and hospital data to trace patients and close contacts, predict hot spots and provide warnings. The article also discusses flood monitoring from multiple data sources including ground sensors and satellite imagery able to predict, monitor, map and simulate flooding scenarios in real time.

Döllner (2020) presents a method for applying machine learning techniques to interpret point cloud data by way of a reformulation of the naturalness hypothesis.

This allows for object classification from point cloud data. The author provides an example using PointNet to classify objects within a street scene into the categories of ground, building, vehicle, pedestrian, or street furniture. Advantages asserted for this method include scalability through use of service-based or on-demand computation and greater storage efficiency due to the removal of pre-built 3D models from the process.

Critical Infrastructure & Construction

Cheng, Hou, and Xu (2023) point out "limited attention" has been given to use of DTs to support emergency management of critical infrastructure "in the context of preparedness, response, recovery, and mitigation" of "natural and man-made disasters" (p.3). The article presents a literature review of 174 articles noting that China is the most active country often with links to US, UK, Australia, Canada and Japan. It defines DTs for civil infrastructure as "dynamic digital replicas of the infrastructure through data from various sources" (p.9). Also, DTs can realise real-time information sharing and management in the construction stage to ensure construction quality and progress. Through intelligent sensing technologies such as machine vision, IoT sensors, and deep learning, DTs can comprehensively monitor the risk factors that will affect engineering quality and make timely adjustments and corrections. For human-machine interactive construction activities (e.g., tower crane hoisting and shield tunnelling), DTs can actively track the personnel behaviour data and estimate the posture of construction machinery, thereby monitoring unsafe construction behaviour. The article can be categorised as one that is ambitious about DTs. It highlights UAVs, Computer Vision and Deep Learning as critical technologies applied in DTs. It notes a five-layer model including the use of 'social sensing' data from social media and remote sensing from UAVs to pinpoint locations and effects of disasters. Also notes DTs are complex and expensive to build possibly into millions or billions of dollars and therefore require strong economic and political drivers. Discusses various resilience theories. On DTs for civil infrastructure emergency management the authors apply a four-stage model: mitigation, preparation, response and recovery. Also notes the cybersecurity vulnerabilities of smart cities and critical infrastructure and the need for cybersecurity to be integrated and notes frontier research in cybersecurity including "deep belief networks, recurrent neural networks, convolutional neural networks, and generative adversarial networks" (p.20).

Community Resilience & Law Enforcement

Bentley (2023) notes the Citizen Safety Digital Twin for Community Resilience project in Warner Robbins, Georgia USA, which "used predictive modelling aided by mobile license plate readers to help police officers 'predict' where crime would occur in the city". Using historical data on crimes in the county the dynamic positioning of ten mobile licence plate readers was successful in reducing crime incidents, with the ultimate goal of proactively reducing crime. Crime rates for burglary, larceny, narcotics and vandalism "correlated with placement of the license plate readers - where the cameras moved, crime rates were lower". The DT was seen as a "force multiplier" by local government that "enabled the police department do more with less".

Oceans & Waterways

von Lukas (2023) discusses digital twins of the oceans, noting that DT research focuses on “man-made” objects rather than living environments (3% of Scopus publications). The article notes the bidirectional nature of DTs and distinguishes them from Digital Shadows and Digital Models, and the growing awareness of the importance of oceans for economic growth, decarbonisation, communication (subsea cables), and transportation. It notes that the Baltic Sea is heavily used and monitored by various industries, “marine traffic, corridors for subsea cables, fishery, offshore wind, military usage, gravel mining and others” which provide a wealth of data. “Digital Twins could be a means to support authorities in examining effects of additional usage and assess the risk of potential conflicts”. The paper discusses the four building blocks of a DT: Observing System (sensors); Data repository; Data analytics and prediction; Interaction (human interface). MARISPACE-X is a joint initiative for a federated data solution. It also introduces unified and immersive visualisation of sensor data that can be used to inspect subsea cables on the seabed, and Machine Learning that can “detect fish or other relevant objects” and enhance images for human experts to inspect. The paper mentions the uses for education but does not explore the uses for security and resilience.

Z. Wu et al. (2021) Present a digital twin of inland waterways designed to help monitor the safety and security of shipping vessels. The system combines a 3D model of the geography, created using drone tilt photography, with BIM models of specific assets, such as locks and bridges. It also incorporates sensor data representing people, ships, waterways and the environment. This includes AIS, RFID and temperature data. The system also features video feeds from security cameras integrated within the 3D scene and augmented with sensor data.

Industrial & Factory Processes

Hu, Shi, and Jiang (2020) begin by noting the importance of power supply to national economies and the growth in size and complexity of power supply systems in line with economic development. Further, power substations cover a large area with a large workforce and that “management personnel cannot supervise the actual working status of the workers” (p.2). A DT solution is therefore proposed that “establishes the digital replica of the power plant station through the three modules of the substation environment, equipment supervision and personnel positioning” (p.5). The DT provides a “mapping relationship between the real physical world and the digital world” allowing continuous monitoring of “personnel and its working content” and through implementation of “electronic fence/work area…the system also can record and alert accidents include personnel enters restricted area personnel operate equipment in violation, and abnormal production data” [sic] (p.4). A “3D visualization” displays “the working state of the personnel in real time”. To further emphasise the surveillance benefits of the system the authors state “The personnel violation information (position abnormality) can form a one-to-one correspondence with the personnel through the positioning tag. Each violation information is paired with the zone of authority. Through such a corresponding form, the detailed information of each violation is recorded, and the offending personnel is quickly determined" (p.6). The effects on staff morale from continuous monitoring of their locations and activities are not discussed, however, the article points out in conclusion that the system design is in a "relatively early stage" and future improvements will allow "Quick alarm for abnormal behaviour of personnel, and optimization of work design through abnormal analysis" (p.7).

Qi et al. (2021) note the pressures on manufacturing of crises like Covid. Supplies of raw materials and labour may stop due to external events. New IT and smart manufacturing can play a role to cope with those challenges with decision support for agile responses. Crises like pandemic, earthquake, flood, drought, etc. drive explosive urgent demands in two classes: medical and basic supplies, e.g. PPE, medicine, temporary hospitals, disinfection supplies, tents, food, bedding, fuel. Exacerbated by hoarding, uncertainty, severity of consequences. These supplies are needed rapidly and must be of high quality for human safety.

Disease & Pandemic

Girotto et al. (2024) examine the link between water-related climatic hazards (WRCH) and outbreaks of life-threatening diseases such as cholera, dengue, dysentery, malaria, and others. Noting the crucial need to predict the occurrence of disease outbreaks in order to prepare contingency plans to reduce risks to affected populations the article gives a critical review of 73 papers on early warning systems (EWS) for climatic hazards. The paper concludes: "a few Large-scale EWS applying geo-spatial data, satellite observations, remote sensing, and advanced modelling tools have been operated to enhance the disease outbreaks prediction" but these should be expanded to more countries, especially in the Middle East and Southeast Asia that are most vulnerable. Further, "Mobile phone technologies, data hubs, and social media platforms play a crucial role in monitoring and detecting affected areas" and "VR, AR, and DTI [Digital Twin Innovations] have garnered significant attention as innovative digital tools for 3D visualisation of hazards. They enhance interactive awareness among relevant stakeholders regarding potential disease outbreak hotspots and contribute to effective management of disease outbreaks to ensure human health safety. However, there remains a substantial gap in the integration of these technologies into disease based EWS used for tracking WRCH" (p13). The paper notes the challenges of obtaining quality data, especially in less developed regions. Also, points out that researchers and developers can easily access APIs, data, and low cost portable sensors, and that "real-time transmission of collected data is easily possible through digital technologies such as LoRaWan, ad-hoc LAN networks, and Wi-Fi" (p.9). This ease and low cost would indicate potentially a low barrier to entry for relevant agencies to begin using these kinds of solutions.

Lu et al. (2021) present an article written during Covid pandemic focussing on managing patient records and medical resources to optimise the deployment of such resources and create "an inter-hospital resilient network for pandemic response based on blockchain and dynamic digital twin". The article emphasises the 'system-of-systems' aspect of regional and local healthcare, where multiple hospitals are interconnected and interdependent. The paper presents a model for identifying systems, subsystems, sections and components of health systems, and types of interdependencies including physical, cyber, geographic, logic, spatial and functional. The article discusses the use of blockchain – distributed public ledgers – to facilitate secure distribution and sharing of patient records, and the use of dynamic DTs to "optimize the medical procedures amongst hospitals in a coordinated way". The authors claim the model is applicable to the Covid 19 pandemic and "manage the crisis in the future".

Lv, Qiao, Mardani, and Lv (2022), also written during the Covid 19 pandemic, present a case study of resilient supply chains using N95 masks as an example. Begin by noting that Covid 19 pandemic disrupted and exposed vulnerabilities of key supply chains. Further, "AI can leverage unstructured real-time data to alert, predict, and analyze outages and vulnerabilities, and recommend corrective actions". Results of the quant analysis show resilient supply chains share suppliers, and have a "capacity repair strategy". Enterprises must realise unpredictability is a new normal, plan in advance, ensure appropriate safety stock, work with trusted, agile partners, and prepare alternative schemes with other ready options.

Pang et al. (2021) advocate "an early and radical government response [as] the most effective method when facing a novel infectious disease" (p.760). They note a significant proliferation of machine learning to provide intelligent forecasting, but these models face the challenge of the long time needed to collect sufficient amounts of data (the 'cold start problem'). They note the tension between data privacy concerns which can lead to data silos, and the need to share data for deep learning to occur across data sources – therefore they propose a federated learning paradigm (FL) to resolve the problem with Time Convolutional Networks, creating a city/state DT providing a digital overview of "city/state facilities, human activities, and other types of information to enable information convergence" allowing prediction, data accumulation and continuous interaction with the physical world. Federated learning involves only the parameters shared among multiple parties without transferring raw data – a central server aggregates contributions to enhance the global model – process repeats until convergence of global model or desired outcome reached, cited examples include Google's Gboard, health AI, and smart banking. Simulation of Covid datasets supports the predictive power of the model and authors note it "can be generalized to other collaborative training problems, such as disaster surveillance and prediction".

Supply Chains

Hassoun et al. (2023) provides a literature review of the application of digital technologies in the agri-food business. It begins by noting the disruption caused to food supply chains by the pandemic and the need to innovate in order to make them resilient, sustainable, and adaptable. It notes eight key digital technology enablers, including AI, IoT, Big Data, AR/VR, robotics, blockchain, smart sensors, and digital twins. The paper notes that "the use of digital twins and virtual or augmented reality in agriculture is still very limited" (p.5). Notes use of IoT, sensors, drones, UAVs for monitoring surveillance of crops and livestock. Tech such as AI can be very useful in predicting disease, yield, soil and weather conditions, but management of large amounts of data can be a challenge, and blockchain for verification and traceability of supply chains and fraud detection including in seafood and dairy industry fraud. Also notes a number of obstacles and challenges; costs, training, supporting infrastructure, silo mentalities, lack of trust/data sharing, data ownership, privacy, security, regulatory issues.

Ivanov (2023) notes the interest in DTs for stress testing resilience of supply chains (SCs) but a lack of guidelines for design of such systems. The author proposes a four-part classification framework for digital twins: model, digital twin, cognitive digital twin (CDT), and intelligent digital twin (iDT). Under this framework a CDT includes self-learning, knowledge creation and transmission, and the ability to make conclusions and recommend decisions. The iDT additionally includes artificial general intelligence and human-AI collaboration. The use of supply chain digital twins within a "stress-test framework" is discussed. The author points to two examples of supply chain digital twins, one built with the Author's involvement for a German retail company (Ivanov & Dolgui, 2021) and the other for a Chinese retail company (Wang, 2022).

In Ivanov & Dolgui (2021), a supply chain digital twin is built in the anyLogisticx supply chain software and used to investigate the impact of the COVID-19 pandemic on the resilience of the food supply chain. The DT simulates ten products, each supplied by three suppliers to 28 supermarket locations across five western and central European countries via three distribution centres in Germany. Five parameters are then varied in the model to simulate four different scenarios based on the COVID-19 pandemic and then compared against the historic data.

Lawless et al. (2021) propose a biosecure DT for resilience of US biopharma manufacturing supply chains in pandemic. They identify insecure architecture as a key vulnerability and propose a Consequence-driven Cyber Informed Engineering approach. In addition to enhanced security, they also identify improved process visibility, parallel cyber-physical modelling, and real-time audits as benefits from this approach.

Cyber Resilience

Salvi, Spagnoletti, & Noori (2022) present cyber resilience of critical cyber infrastructure using DTs – a case study of the electric power ecosystem. The article presents the case for the use of DTs to build resilience of Critical Cyber Infrastructure (CCI) (energy, telecommunications, finance, health, and transportation). It notes the importance of CCI as the backbone of industry, and cascading impacts in the event of outage: "severe consequences and widespread negative spillovers to entire political and economic systems, even threatening national security" (p.2). Notes potential of DTs for simulations, training of personnel and strategic decisions. The authors note a lack of a multilateral information sharing framework, and recommend CCIs should use DTs to "collect, generate, and process the data necessary to provide accurate and timely feedback to all parties" (p.5). Notes regulations are norm setting, and that the article is conceptual rather than technical, and further proof of concept is required.

Bagrodia (2023) Network DTs for cyber resilience of US military missions. Noting the limitations of virtual machine (VM) approaches to military mission cyber security the authors investigate the use of network digital twins to improve cyber resilience of military (combat) systems from a mission-centric perspective. Considers EXata as a specific example of a network DT. Concludes that DTs offer a number of benefits including integration of cyber and kinetic domains, granular data collection, integration of live software and hardware, a persistent model that serves as "an authoritative source of truth" (p.105) and support over entire product lifecycles. The Network DT approach combined with VM-based cyber ranges presents a "best of both worlds" solution to Cyber-Physical Systems (CPS) security.

Epiphaniou et al. (2023) DTs for modelling of CPS IoT vulnerabilities. The research focuses on the benefits and challenges of integrating cyber modelling and simulation with digital twins and threat source characterisation methodologies towards a cost-effective security and resilience assessment. The authors show how adversaries can utilise cyber-physical systems as a point of entry to a broader network in a scenario where they are trying to attack a port.

Weather, Climate Change & Flooding

Jang and Jung (2023) note the increasing frequency of extreme weather events including storms, typhoons and flooding that can damage infrastructure and cause fatalities. They note the need for enhanced flood monitoring, that is more reliable and able to react rapidly in emergency situations, for sustainability, resilience and liveability in smart cities. The authors propose a novel technology that is based on "subminiature low-power IoT technology based on an industrial radar sensor" combined with signal processing algorithms that is capable of detecting with high precision of 1cm and detecting flow energy which overcomes many of the obstacles of conventional technology does not rely on lighting and is able to be installed anywhere, such as CCTV monitoring, and enables predictive alarms and responses.

Riaz, McAfee, and Gharbia (2023) DTs, 3D modelling and Early Warning systems for climate resilience in smart cities. Article identifies 37 case studies in the literature 10 on DTs, 14 on 3D modelling and 13 on EWS. Notes the discussion is mostly conceptual and large gaps remain regarding implementation and use of bidirectional data flows.

Rodrigues da Silva et al. (2023) present the River Cure portal as a web GIS platform for modelling, simulating and analysing flood events. The portal streamlines the current hydrodynamic simulation process using a collaborative digital platform. Users define the context and geometry of their simulation, associate the context with sensors, and can then simulate and analyse different hydrodynamic events. The platform is built using Django, GeoDjango, PostgreSQL and PostGIS and is integrated with the HiSTAV simulation tool, although it provides compatibility with other tools. The authors provide a demonstration of the process with a simulation of the 2016 severe flooding of the Águeda river in Portugal.

Response

Emergency Services & First Responders

Kwok et al. (2021) note the innate hazards of chemical plants and the potential for catastrophic emergencies including toxic release, explosion or fire. Therefore, there is a need for regular training for emergency response (ER). Further that reality in simulations of emergency response is vital. They therefore recommend the combination of virtual reality and DTs in designing ER training and that it is an under-researched area, and that perceptions about the use of VR for crisis management training will determine the adoption or rejection of the technology by users. The study created a prototype ER training where front-line responders used VR head mounted displays (HMDs), and senior staff were able to monitor the scenario using tablets, PCs and mobile devices. DT provided real-time data from IoT devices. “VR devices continuously display updated information about the emergency to the trainees. Trainees can also take action via those devices. Their commands are sent to the simulation model via the intranet, and the simulation model can instantly compute the development of the situation based on their actions”. The study underlines the usefulness of combined VR and DT tech to simulate emergencies for training, and that the user’s perceptions about the ease of use of the tech will be key to adoption, therefore the authors advise careful attention to the user friendliness of the interface, and training prior to the simulation.

Park et al. (2018) propose an “AR-based Smart Building & Town Disaster Management System” that enables faster responses in fire emergencies in multi-storey buildings in smart cities. The system uses IoT devices including electric leak detectors, temperature and humidity sensors, network cameras, multi gas and dust detectors, flame detectors, gas leak detectors and gas valve breakers that improve response times for rescuers, and provide evacuation guidance to occupants, and provide real-time information to fire department responders.

Smit, Voûte, and Verbree (2021) 3D first responder simulation using AR headsets. Dutch study presenting a proof of concept (PoC) for spatial awareness through mapping of indoor spaces (in this case an office) through the use of head-mounted Microsoft Hololens units worn by first responders in an emergency response scenario. Study assumes that WLAN connection would be difficult in an emergency and uses a 4G connection via cell phone hotspot. Article notes the complex, urgent and dynamic nature of emergency situations, and the need for situational awareness that provides, perception, comprehension and projection of the situation. Projection is emphasised as the ability to predict future states. The Hololens using a depth camera and Mixed Reality Toolkit (MRTK V2) is able to create 3D mapping of the space capable of recognizing and differentiating walls, floors, and objects in real time and able to be monitored by the emergency response coordinator. The article found that the model provided reasonable accuracy, precision and robustness. Different viewing modes, and colour coding of the 3D display presented newest data in contrast to older data, identified navigable space for the responder, and tracked the position of the responder moving through the environment. Feedback from first responder practitioners confirmed the value of the model, and emphasised the need for it to be able to identify and highlight particular objects like Exit signs, victims, and light switches. Some gaps in the mapping were seen as the Hololens is only able to map up to 3 meters from the camera.

Wong & Lee (2023) look at fire emergency response. Article on smart emergency response to fire emergencies in high rise buildings. Presents a Collaborative Response (CORE) model to enable indoor navigation across multiple floors, to facilitate location of victims, firefighting resources, exits, and route planning. Uses a data fusion approach with BIM (Building Information Management)-driven pathfinding and particle filter-based positioning, with wifi antenna, barometric measurements for altitude, accelerometer and gyroscope, step length estimation, to pinpoint locations of responders. Authors claim a pathfinding algorithm that is "89.29% more efficient than the conventional Dijkstra's algorithm" (p.16) reducing computational time. And that the study "makes one of the first attempts to leverage IFC [Industry Foundation Classes] emergency-related properties and establish a real-time information exchange mechanism for on-site emergency response".

Ribeiro, Gonçalves, & Bartolomeu (2023) DT migration – a use-case for emergency vehicles. This Portuguese paper focusses on autonomous emergency response vehicles and implementing a DT of the vehicle fleet, combined with edge node computing to reduce latency and increase bandwidth. Portugal's National Institute of Medical Emergency has 10 types of emergency response vehicles, including common ambulance, medical emergency and resuscitation, and catastrophe intervention vehicle capable of "setting up an advanced medical post" (p. 66). Creating DTs of all vehicles in the network, combined with the equipment and staff carried in each vehicle allows dynamic allocation of vehicles depending on the nature of the emergency. The authors describe a medical emergency scenario "requiring immediate intervention for which the initially dispatched vehicle and medical professional are not equipped to deal with and a new specialized vehicle and EMT" are needed. DT containers with all relevant details of emergency vehicles could reallocate a specialised vehicle and team and compute the best location for the vehicles to meet and transfer the patient.

Traffic Flow & City Incident Management

Wolf et al. (2022) present a DT for multi-agency incident management in smart city. Article from Newcastle University researchers, so is directly relevant to UK context. Takes a use case of a road incident on the Tyne Bridge connecting two cities; Newcastle and Gateshead. Emphasises systems engineering approach to design with end user in mind. Conducted interviews with multiple emergency response agencies and emphasised the need for DT to integrate heterogeneous data sources from multiple sources to facilitate a multi-agency response. The prototype developed using Microsoft Azure automates several processes that were identified by stakeholders as being of use and presents them in an API visual user interface; identifying the location of an incident and a buffer zone (200m in this case), identifying locations of responders from different agencies (ambulance, police, fire), identifying closest responder and fastest route (integrating latest data on traffic, weather, roadworks), estimated time of arrival, notifying all stakeholders when the responder vehicle has entered the buffer zone, updating all stakeholders of the response, and ETAs of further responders if needed, notifying all stakeholders when the responder vehicles have left the incident and roads can be reopened (for traffic management stakeholders). The prototype presents "initial functionalities" but the study points out that it can be expanded with further data sets and to different functionalities "For instance, during a storm event affecting various city domains, stakeholders can receive transport updates from CCTV cameras and sensors48, Twitter posts (about ongoing road incidents), rainfall data49, food warnings50, and stakeholder calls. Although all data are in different formats, they all include incident-relevant information that needs to be aggregated in real-time" (p.9). It recognises but does not discuss in detail proprietary issues around data ownership. It references JESIP (Joint Emergency Services Interoperability Principles). It includes a useful set of questions that were asked to emergency services responders to identify steps in their processes.

Wu et al. (2022) DT for tunnel maintenance. Notes importance of tunnels as a vital component of traffic infrastructure, with high requirements for safe operation and traffic flow. Includes useful literature review on various approaches to tunnel monitoring technology across Europe and Asia. Noting difficulties in tunnel surveillance due to video "fragmentation", the separation of video data and service data, and of 2D and 3D models, the authors propose "a novel tunnel digital twin construction" (p.2) using BIM, IoT data and real-time "video fusion into 3D virtual scene" combining static and dynamic data to facilitate "tunnel traffic flow, accident rescue, facility management, and emergency response" (p.6). Article considers a tunnel in China as an example and claims to demonstrate several of the advantages of the approach including "virtual top view global monitoring, automatic tunnel video patrol, two- and three-dimensional linkage emergency response" (p.20) but notes several disadvantages such as need to calibrate cameras one by one, "two-way interaction functions of virtual and real models need to be realized, the video data structure algorithm lacks integration, and so on" (p.21). (Preparedness and response)

Gkontzis et al. (2024) urban resilience (efficiency) through smart city data analysis. The article presents a prototype Smart City DT for the city of Patras, Greece, created using a custom Python solution coupled with Flask micro web framework. Data for the citizen-feedback DT is based on five years of historical data (93k reports) from the Sense City platform launched by the Patras municipal government in 2018, allowing citizens to make reports about issues. The platform separates these into eight categories of issues (garbage, lighting, road constructor, green, protection policy, environment, plumbing, and parking). Backend software anonymises data, and includes information on time, location, type of issue. The user interface visualises the data with colour coding for type of issue on a dynamic city map combining historical and real-time data. Users can zoom in and interrogate the data. Further utility is provided using Machine Learning employing the random forest classifier, the authors claim they are able to provide predictions up to 6 months ahead regarding the type of issue, probability and location. The "proposed analysis adds a crucial dimension to issue tracking, enabling city officials to discern evolving patterns and make informed decisions". The authors note the absence of standardised protocols for seamless data sharing across systems and platforms. Also, the heavy reliance of ML on historical data that may contain biases. The ability of the system to cope with a major "black swan" event such as a terrorist attack is not specifically discussed, although the platform "protection policy" as a category does not discuss specifics of what this covers. The literature review references smart city DTs in Dublin Ireland, Malvalaan Netherlands, Jakarta Indonesia, Milan, Wuhan and Macao China. Many emphasise the need to determine the needs and expectations of citizens regarding SCDTs, and the need for high quality data.

Fan, Zhang, Yahja, & Mostafavi (2021) provide an overview of a vision for a "disaster city" digital twin paradigm, with an emphasis on the roles of AI and ML techniques. This consists of crowd sourced mapping, humanitarian network dynamics, data integration and analytics, and gaming and visualisation. They discuss three kinds of data collection: remote sensing using drones and satellites, with AI providing semantic context and object detection; social sensing using natural language processing of social media; and crowdsourcing. They also discuss the potential for serious gaming as a training tool for responders, and dynamic network analysis to increase the visibility of the interactions between different actors competing for resources during a disaster.

Hospitals

Rodríguez-Aguilar and Marmolejo-Saucedo (2020) propose a conceptual model for integrating digital twins with multi-paradigm modelling for planning the management of health services in the event of public health emergencies. They note "there is no health system fully prepared for unexpected contingencies such as public health problems due to natural phenomena, catastrophic events or epidemics" (p. 2) and in the face of a public health emergency "the health system must operate in a coordinated manner to optimize resources". The model includes Agent-based simulation and the multi-paradigm approach (at the macro, meso and micro level) for discrete and dynamic simulation scenarios. The authors propose a digital public health emergency system with Twin Hospitals: exact replicas in the digital system "allowing information to be integrated in real time through smart devices that allow monitoring the demand and provision of health services, as well as the evolution of the state of health of the patients. The information collected will be integrated through data and process mining, generating real-time dashboards" (p. 8) enabling traceability of each patient (important in epidemics). Each Hospital Twin has an interface that allows the interaction of decision makers with the digital system and in turn extract knowledge to define prospective lines of action. Using smart sensors to collect real-time information the authors claim it is possible to optimise the allocation of resources including drugs, equipment, and human resources in the event of a public health emergency. The article provides only a conceptual framework and does not provide specific details on how such a DT would be constructed.

Basaglia, Spacone, van de Lindt, and Kirsch (2022) note that in the case of disasters like a major earthquake hospitals face “a sudden surge of incoming patients, that can directly impact their ability to provide adequate care” (p. 2). The article sets out the *surge capacity* of a hospital defined as the maximum potential delivery of resources: system, space, staff and supplies. Where “surge capacity exceeds surge, the surge response capability is greater than 1 and the hospital is deemed to adequately respond to the disaster” (p. 2). The article examines the PEIMAFs (Internal Emergency Plan in case of Massive Influx of Patients) of hospitals in Italy and constructs a discrete event simulation of a post-earthquake event and the response of a small hospital in central Italy. The “simulation results show that the main parameter contributing to critical mortality is the delayed treatment” (p.17). The study may be of limited utility to a scenario of a different kind of health emergency such as a bombing or fire, due to the different nature of the injuries and responses. This study while it mentions digital twins of hospitals appears to present only a simulation study as distinct from a true DT with bidirectional information flow between the digital and physical objects.

Earthquake & Flood

Yu et al. (2023) DTs of urban earthquake disasters. Earthquakes are not one of the scenarios considered for this project, however, methods used to simulate urban environments, and the damage caused by disasters, may be applicable to other scenarios, such as fire and flood. In this study the authors establish three-dimensional urban scenes using satellite data, oblique photogrammetry from UAVs, LiDAR, and “other space–sky–ground three-dimensional digital acquisition methods” (p.5). Combined with recorded data of building height, structure, layers, materials, and historical data of seismic intensity of earthquakes in the region, the authors simulated the damage caused by earthquake on buildings and conclude that the DT method can “propose prevention and control suggestions” and inform “efficient emergency rescue” solutions (p. 19). The study as presented is a simulation, however, the authors envisage using DTs in real-time earthquake responses, while acknowledging “in the case of an earthquake that damages the network base station, monitoring ability is lost, and a real-time digital twin cannot be realised” (p.19).

Tarpanelli et al. (2023) look at the use of satellite data for delineating flood hazard maps. They use the context of a 2017 breach of a levee on the Enza River in Italy, to compare the performance of maps generated using Synthetic Aperture Radar (SAR) against those using optical data. The former is often more available, as optical data is impacted by cloud coverage which is commonly associated with flood events. These maps were then compared against maps generated using the WEC-flood model with different Manning roughness parameters. The optical data had significantly higher agreement with the model (c.a. 75%) than the SAR data (c.a. 55%). The researchers noted that rough surface water is hard to distinguish using SAR data.

Recovery

Ghahari et al. (2022) highly technical article that presents a novel model for "bridge digital twinning and virtual sensing through the application of an output-only time-domain model updating technique for post-earthquake damage diagnosis". The model offers an evolving and live platform that can be used for response prediction, asset management, rapid post-earthquake damage assessment, and decision-making for maintenance/rehabilitation of bridge infrastructures in post-earthquake emergency response scenarios.

Resilience of DTs

Fogli et al. (2024) examines how "chaos engineering" can be applied to improve the resilience of DTs, and the feasibility of assessing the resilience of a proof-of-concept DT through a testbed based on widely adopted, open-source tools.

Alcaraz and Lopez (2022) note the positive impact on value chains of industry 4.0 and DTs with simulation capabilities able to forecast, optimize, and estimate states and configurations. Further, that DTs are based on a composition of technologies, cyber-physical systems, IoT, edge computing, AI, virtualisation infrastructures, big data. Article stresses the *bidirectional* nature of DTs and the "confluence of all these technologies and the implicit interaction with the physical counterpart in the real world generate multiple security threats that have not yet been sufficiently studied" (p.1475). The DT can execute commands that change the state of the physical counterpart, when automated can make decisions, for products, processes or systems, therefore they can be considered critical systems. And, they contain intellectual property which represent the digital copy of the physical world. The article sets out the significant number of cybersecurity threats that could apply to DTs including software attacks, privilege escalation, extraction of private information, rogue CPS/IoT devices, digital threat tampering, Man in the middle, Denial of service, physical attack and others. It also explores a number of security approaches including HW/SW security, hardening DT infrastructures and decoupling, identity authentication, intrusion detection, response and recovery, and others.

Holmes et al. (2021) recognise both the "insufficiently explored risks of the integration" of DTs into manufacturing, construction, agriculture and transportation, but also the opportunities for the DTs themselves to mitigate cybersecurity risks and become an integral part of a security in-depth defence. They note "given the bi-directional link between the two [PT and DT] an attacker may negatively affect both through changes in either. However, this also presents an opportunity to identify malicious changes" (p.4). The article examines the types of cyber challenges created by DTs and Cyber DTs, such as data/IP leakage, Confidentiality, Integrity and Availability (CIA), but also the ways DTs could solve cybersecurity challenges; improved patch management, advanced system and security testing, training and incident response.

Jin et al. (2022) summarizes the results of a 2021 Society for Risk Analysis "Workshop on Resilience Analytics" for Cyber-Energy Systems. It notes cyber-physical systems in multiple system domains e.g. water, energy, networking and that resilience is "notably absent" from the NIST guidelines for cyber and engineered physical elements. A review of research on CPS found a focus on efficiency and a conflation of risk analysis and resilience; only 11% focus on recovery capability as an aspect of resilience. Risk hardening is not enough, ultimately a system will fail, whether by accident or attack, and it must be able to recover. Recovery entails redundancy, (e.g. redundant sensors to replace damaged sensors) and is not the most cost efficient option. Article discusses the challenges of integrating systems of systems across multiple domains. Notes the role of AI/ML and two future research directions 1) Pareto concept for multi-objective system optimization and 2) reinforcement learning on digital twin models for resilient decision making. Also notes a lack of analysis across interconnected systems, and the US Army's Framework Integrating the Complexity of Uncertain Systems (FICUS) tool that integrates data from many domains to project how disruptions propagate across systems.

Additional Articles

Two highly relevant articles were added at the conclusion of writing the literature review as they were released during the first phase of the project.

Li, et.al. (2024) This article does not use the term "digital twin" however it gives detailed attention to simulating flooding across Shanghai's urban road network using mobile phone data of cross-city commutes of the local population. The simulation of flooding of varying intensities from 10-year to 500-year floods demonstrates the ability to identify vulnerable sections of roads liable to experience overcapacity, and hence the cascading effects on congestion, even on roads not directly exposed to effects of the disaster. Some policy recommendations can be drawn from this such as the need to enhance the *overall* resilience of the road network, rather than focussing solely on disaster-exposed areas, increasing redundancy of arterial roads and "strategically optimiz[ing] the density of urban branch roads to ensure redundancy in the road network" (p.17).

Wang et.al. (2024) note that some studies have been done on DTs for urban resilience, but the area is still "in its infancy" (p.35). Notes 3D and 4D modelling projects in Singapore, Western Sydney, West Cambridge, and Dublin Port. Focusses on predicting and reproducing effects of disasters in the virtual space, and the research challenges of: mapping building and city information from reality to virtuality; how to accurately predict and simulate disaster processes for buildings and cities; and using simulation in prevention and mitigation strategies. The body of the article focusses on novel techniques to combine low res and high res data sources to give accurate mapping of cities and simulating damage from earthquake, fire and wind. The authors present a multi-hazard DT platform for their university campus integrating data from buildings, trees, water and electricity systems, and a case of study of accurate prediction of actual tree damage that was predicted and subsequently occurred in the campus area. The article outlines potential benefits from DTs across the resilience stages including pre-disaster planning, real-time emergency assessments, post-disaster rescue operations, and accident investigation.

Appendix B: Quantative Summaries of Article Metadata

[Note that the following figures were created in September 2024 and do not account for any references added during the revision process]

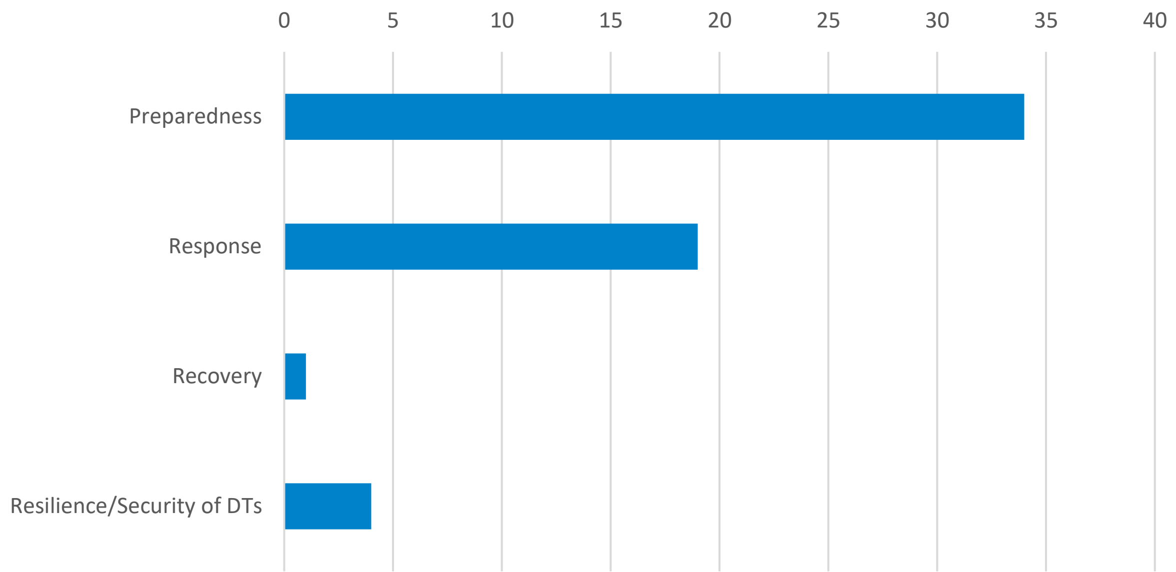

Figure 5: Number of articles by Resilience Type. Note some articles fall into multiple categories.

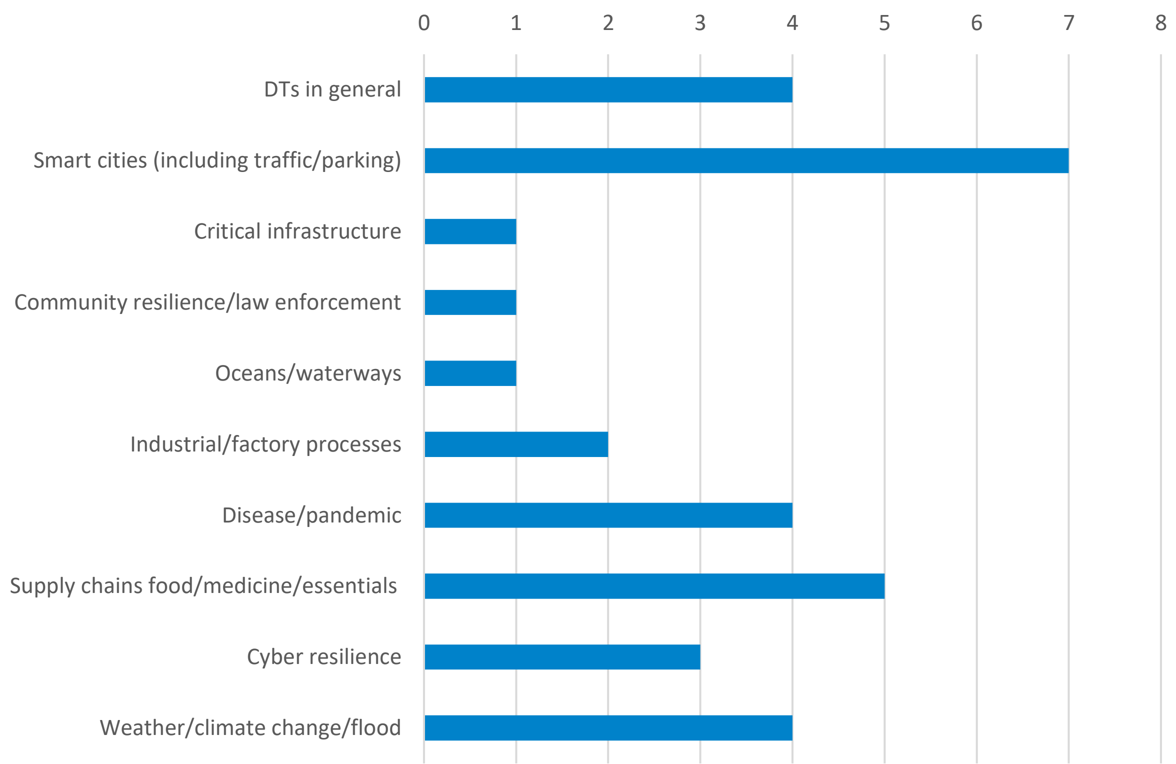

Figure 6: Number of articles by domain/sector for Preparedness

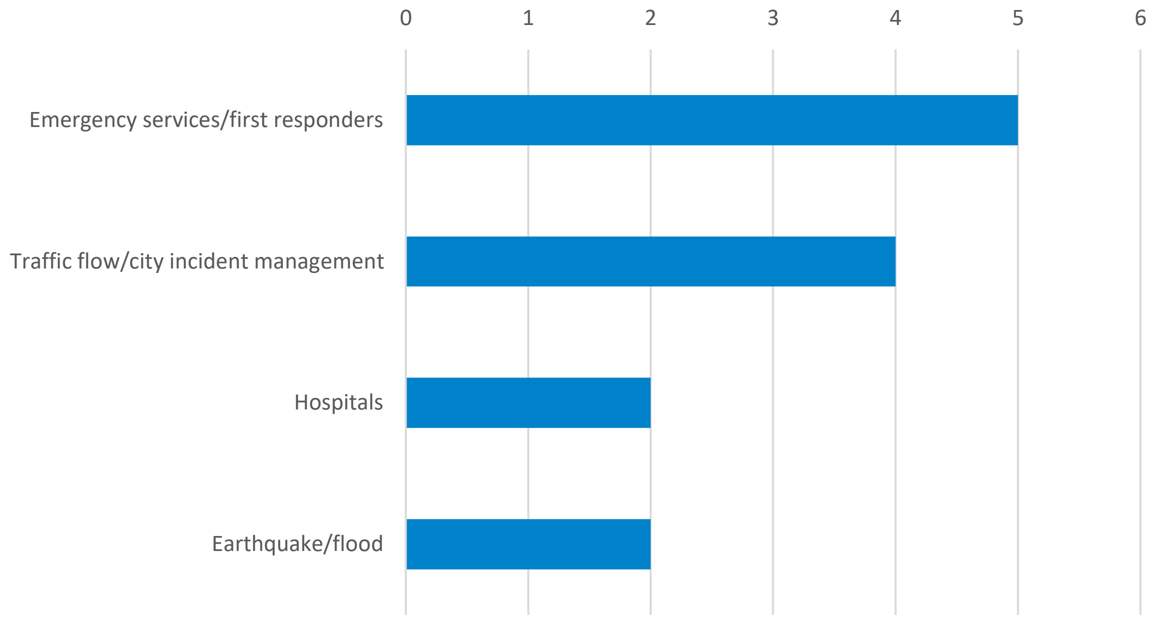

Figure 7: Number of articles by domain/sector for Response.

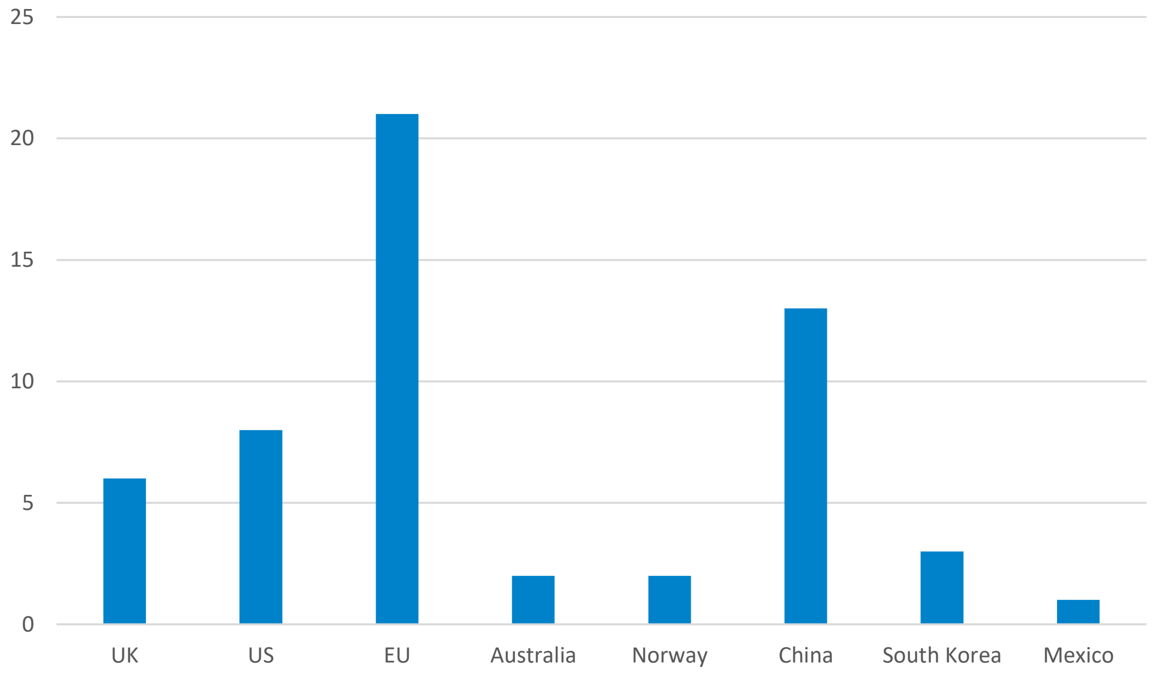

Figure 8: Number of articles by country of origin of research institution

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