TWINNING FOR DECARBONISATION

Internet of Things Enablement for Transport Digital Twins

AUTHORED BY
Natalia Lukaszewicz
Cade Wells
Helen Sandison
Shrawan Jha

Twinning for Decarbonisation

Internet of Things (IoT) Enablement for Transport Digital Twins

About this report

The aim of the report is to explore and understand the current state of digital twin technologies around physical and digital infrastructure – driven by the Internet of Things (IoT) technologies – as well as cybersecurity. The report provides a techno-economic context for digital twin implementation in transport, its adoption within different transport modes, and importantly, its integration with the energy network.

Acknowledgements

This report was commissioned by University of Glasgow and authored by CENSIS, Scotland's Innovation Centre for sensing, imaging and Internet of Things (IoT) technologies. It is part of the consultation process within the 'Twinning for Decarbonising Transport' TransiT programme. We gratefully acknowledge the support of the authors.

Contents

List of tables

List of figures

List of pictures

Executive Summary

This document contains a technology landscape review examining the role, maturity, capability and future opportunities for digital twins in the transport sector including challenges, gaps and barriers. Emphasis is given to the potential for digital twins to influence the decarbonisation targets of the sector. This landscape review has been developed as a preparatory document to a proposal by the University of Glasgow for a National Digital Twin Hub tender by EPSRC/DfT.

Definition: A digital twin is a virtual replica (model) of a physical asset that emulate the life of a physical entity. A physical asset can be a component, a device, a process, a system, even a full supply chain, as well as a human behaviour. The digital replica is created by collecting and integrating data from various sources, such as sensors, IoT devices, and simulations, to model the real-world entity in a digital format. Each digital twin is linked to its physical twin – the stream of data/information is bidirectional. This means that the digital twin can also interact with its physical twin and "send back" commands to initiate changes to its real-world entity.

A digital twin is not a single technology but a bundle of various software- and hardware-based tools that together enable a digital twin system.

The key characteristics that make up a digital twin are the ability to interpret multiple data streams, the ability to monitor assets and processes in real time, closed loop feedback, visualisation of the assets or processes, and the capability of forecasting the response of the real-world twin in response to changes in its digital equivalent. The infrastructure for any digital twin can be separated into the cyber-physical environment and the data environment. Although there are common elements, the implementations will vary across road, rail, maritime and aviation.

There are several emerging technologies which have significantly advanced the capabilities of digital twins in the last ten years. These include IoT (Internet of Things), edge processing, advanced analytics (including AI and Big Data), cloud computing and storage, and Virtual and Augmented Reality. These capabilities can impact process efficiency, productivity, and energy consumption. In transport, they can optimise routing and scheduling, incident response, and enable predictive maintenance of equipment. The forecasting and simulation aspects allow operators to run scenario planning for risk management and event preparation.

All successful implementations of digital twins have two key characteristics: adaptability and scalability. The real-world changes so quickly that without these being built-in from the start, a digital twin can quickly become out-of-date and obsolete.

The total cost-of-ownership of an implementation will vary by scale but can run to hundreds of thousands of dollars. It is essential to quantify the benefits with respect to the costs and build in KPIs to monitor progress. For example, we show evidence that the use of digital twins can help reduce a city's carbon footprint by up to 35%. Other benefits may include new service models resulting from the data generated by the twin. An interesting example is the Rolls-Royce "Power by the Hour" scheme for engine maintenance management that was a novel solution back in 1962 with a fixed rate per flight hour basis and is now well adopted in the industry. Its upgraded version Rolls-Royce CorporateCare® services with integrated sensors and real-time data collection reduced jet engine maintenance by 1/3 and increased engine efficiency, saving 22,000 tons of carbon to date.

The introduction of IoT and new communications standards such as LPWAN, 5G and Satellite have revolutionised telematics and revealed new opportunities in route optimisation, "just-in-time" delivery models, and autonomous vehicles. These diverse communications options often lead to

hybrid deployments balancing the various needs of the solution according to requirements such as bandwidth, sampling rate and latency considerations.

Challenges in the introduction of digital twin systems remain in the areas of interoperability and standards, as well as “trust” in data sources, for example from sensors due to issues with calibration and drift.

The heterogenous nature of the data collection from multiple sources increases the risks associated with privacy and security, amplified by the lack of common standards.

The data environment manifests other significant challenges. Data storage and processing uses a lot of energy. It is important that the decarbonisation benefits of digital twins outweigh their associated carbon impact.

The development of new tools and techniques can help overcome many of these challenges with shared immutable ledgers such as blockchain for security, compression methods for data handling, AI approaches for analysing for large datasets, and edge processing on local devices to reduce communication bandwidths. Enhanced security can be provided by the use of Private Cloud rather than Public Cloud storage.

Advances in data processing techniques have introduced a raft of new products such as distributed storage and processing (Hadoop, Spark) and algorithms and libraries for machine meaning (Mahout).

Essential to the use of Digital Twins are visualisation tools and methods. Examples include Geographic Information Systems (GIS) for real-time mapping of transport infrastructure (roads, railways, public transit) along with information overlays. Dashboarding platforms based on solutions, such as Tableau or Power BI, can present real time data in easily digestible graphical formats. Simulation tools (Simulink, Witness) have their roots in mathematical modelling from Operational Research and are used for predicting the output behaviour of a system to variable inputs. This is useful for forecasting the response of a transport network to non-standard operating conditions. While Virtual and Augmented Reality (VR/AR) methods allow users to examine this digital multi-dimensional environment interactively.

Transport systems will become increasingly reliant of the operation of digital twins for their operation. It is critical that this functionality remains as close to uninterrupted and error-free as possible. Key to this is the use of cybersecurity. Some of the barriers to effective security include ageing and legacy infrastructure, the size and diversity of partners, the quantity and range of data types, exposure to physical attacks and the use of proprietary “black box” technology, opaque to users. The risks from cyber-attacks include categories such data theft, data corruption, data poisoning to reduce functionality or indeed permanent damage. All of these have the potential to compromise transport safety.

Due to the complex nature of digital twins, a “systems approach” to security and resilience is recommended. Emerging standards, frameworks and best practice include “the Gemini Principles”, a “secure by design” value set for digital twins focussed on addressing security from the outset, and the consequential “Information Management Framework (IMF)”, enabling secure data sharing and effective information management. The adoption of such frameworks into practical and implementable steps by organisations (Maturity Model), together with a self-assessment methodology will become a fundamental requirement for digital twins as standards are agreed and effected. Future work in this area is needed in standards mapping and consolidation, multi-domain security coordination, and trade-off management for emergency events.

The case studies and projects detailed in this document demonstrate common ambitions and challenges for the transport sector. The ambitions centre on transport efficiency, seamless interoperability with other infrastructure, cost and energy reduction, and new service innovations. The challenges include adaptability and scalability as a result of growing complexity, system resilience, data integrity and security, and the increasing financial and computing investment required for deployment and operation. With this in mind, we stress the importance of developing strong business cases for digital twins including a comprehensive Return-on-Investment (ROI) analysis.

The document concludes with a detailed gap analysis across the transport digital twin landscape and identifies opportunities for further academic research. Some examples of this include adaptation to new infrastructure and modes, such as the use of hydrogen and electrification in transport; research on resilience to "black swan" events; the cultural impacts on digital twins in organisations; the mitigation of errant human interfaces in digital twin solutions; the use of closed and open data streams for new products and services; and many more.

1. Introduction

This report has been commissioned by Prof. David Flynn, University of Glasgow, as part of the consultation process within the 'Twinning for Decarbonising Transport' TransiT programme.

The aim of the report is to explore and understand the current state of digital twin technologies with regard to the physical and digital infrastructure – driven by the Internet of Things (IoT) technologies - as well as cybersecurity. The report provides a techno-economic context for digital twin implementation in transport, its adoption within different transport modes, and importantly, its integration with the energy network. As the focus of the TransiT programme is decarbonisation of transport, this important theme is investigated from various angles throughout the report.

Importantly, the main objective of the report is to identify the open questions and challenging topics that create research opportunities to improve digital twins in terms of their interoperability and scalability and to foster their adoption in the industry. In all these activities, decarbonisation is at the forefront, with a view to reducing CO2 emissions from transport, but also to constructing and maintaining the digital twin infrastructure in a "green" and environmentally friendly manner.

The report offers a more practical than theoretical perspective on the technology field of digital twins, i.e., it examines what technologies are in use, and what needs to be done to encourage wider technology adoption, by providing several case studies and various practical examples.

The report consists of eight chapters structured in the following manner:

- Chapter 2 introduces the concept of a digital twin, its definition and the main characteristics a system should have in order to be recognised as a digital twin. It also explains the role of Internet of Things (IoT) technologies as a key enabler of digital twins and the role of IoT in decarbonisation activities as well as in intelligent transport systems..
- Chapter 3 focuses exclusively on the transport digital twin, the benefits from the technology, the value creation, the implementation costs, and the environmental aspects of digital twins.
- Chapter 4 examines the state of the art of the digital twin physical infrastructure: device layer, connectivity, system integration and interoperability requirements. It explores questions such as the required scale of system deployment, the required system architecture, and how to ensure data quality generated from devices.
- Chapter 5 examines the digital infrastructure components such as data storage, required computational power, edge/cloud computing, as well as visualisation tools.
- Chapter 6 covers the critical topic of cybersecurity and investigates the state of the art of cyber-physical security and resilience of networks of digital twins, the availability of standards, and protocols.
- Chapter 7 presents case studies to illustrate the profound impact of digital twins on the transport industry, showcasing the broad spread of real-world examples that present the practical applications, benefits, and challenges of digital twins in transport, highlighting their role in enhancing efficiency and sustainability.
- Chapter 8 gives an overview of the PETRAS IoT projects conducted by the National Centre of Excellence (a consortium of 24 research institutions and the world's largest socio-technical research centre focused on the future implementation of IoT).
- Chapter 9 provides a list of recommendations for the research based on the findings from the earlier sections.

2. WP1 IoT-Enablement for transport digital twins

2.1. Defining a digital twin

Intense attention has been directed at digital twins in 2023, as they move from the 'early adoption' stage to the mainstream in terms of interest, investment and overall technology acceptance (Atos, 2023), and also appear to represent another technological milestone towards a multi-dimensional digital experience - the Metaverse. Given the extent of the discussion and chat about digital twins, be it in the context of research, prototype testing or commercial use, it's important to define what is meant by it.

This report therefore begins with a cohesive definition of the digital twin and the main characteristics a system should have in order to be recognised as one. Before constructing this definition, we look back at the evolution of the digital twin concept.

The idea of a digital twin was born in the 1960s at NASA where a 'living model' of the Apollo mission was constructed in response to Apollo 13's oxygen tank explosion and subsequent damage to the main engine; NASA employed multiple simulators to evaluate the failure and extended a physical model of the vehicle to include digital components, thus creating a 'mirroring model'. This allowed for the continuous ingestion of data in order to model the events leading up to the accident, for forensic analysis and exploration of next steps. NASA engineers completed the process in under two hours and saved the lives of the three astronauts on board. (Allen, 2021; Uri, 2020)

Decades later in 2002, the concept of a digital twin was introduced by Michael Grieves for the formation of product lifecycle management. At the time, it was called a 'Mirrored Spaces Model' and started from the notion that a "digital informational construct about a physical system could be an entity on its own. This digital information would be a 'twin' of the information that was embedded within the physical system itself and be linked with that physical system through the entire lifecycle of the system." At the time, Grieves defined all core elements of what later became known as the 'digital twin': real space, virtual space, the link for data flow from real space to virtual space, the link for information flow from virtual space to real space and virtual sub-spaces. This led to the digital twin being defined as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin" (Grieves & Vickers, 2017).

NASA defines a digital twin as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic (…) In addition to the backbone of high-fidelity physical models, the digital twin integrates sensor data from the vehicle's on-board integrated vehicle health management (IVHM) system, maintenance history, and all available historical/fleet data obtained using data mining and text mining" (Glaessgen & Stargel, 2012).

In the Digital Twin Roadmap 2035, a digital twin is defined as "a model with real- or right-time two-way information flows, enabling the implementation of autonomous decision making. This can provide autonomous optimisation, and remote and autonomous operations".

Rolls-Royce, which produces engines used in aviation, currently utilises digital twins to fine-tune its engines and simulate a variety of conditions, and uses the term the 'Intelligent Engine'. It explains digital twins as "comprehensive, interoperable virtual representations of physical objects, processes or systems. Digital twins in our business sectors are shaped by the data on features such as the performance, condition, and operating environments of their real-world counterparts. When AI-enabled, they can learn from data patterns and autonomously interact with their physical twins to make beneficial operational changes" (Rolls-Royce, 2023).

The common theme in the application environments from the above definitions is the generation of huge amounts of data from sensors, smart devices, documentation, construction drawings and more. The digital twin captures this data from products and assets and analyses it to provide actionable insights for informed decision-making. In other words:

- Digital twins enable complex analyses and simulations to be performed and systems to be monitored.
- They provide transparency and clarity through data sets.
- They can use historical context and performance data to understand the past and predict the future.
- The direct and indirect data is processed into patterns using machine learning, and the patterns can then be used to gain insights.

Digital twins are regarded as a prerequisite for the functioning of Industry 4.0 and a central point for its success. Thanks to digital twins, an entire logistics network could be represented virtually by recording all structural information, such as locations, capacities and characteristics of warehouses, distribution and processing centres, as well as process data.

For the purpose of this report, and based on the information above, the following definition of a digital twin is adopted:

> **A digital twin is a virtual replica (model) of a physical asset that emulates the life of a physical entity. A physical asset can be a component, a device, a process, a system, even a full supply chain, as well as a human behaviour. The digital replica is created by collecting and integrating data from various sources, such as sensors, Internet of Things (IoT) devices and simulations, to model the real-world entity in a digital format. Each digital twin is linked to its physical twin – the stream of data/information is bi-directional. This means that the digital twin can also interact with its physical twin and 'send back' commands to initiate changes to its real-world entity.**
>
> **A digital twin is not a single technology but a bundle of various software- and hardware-based tools that together enable a digital twin system.**

It is important to note that simulations, agent-based modelling, visualisations and prototyping can be recognised as subsets of digital twins. Although they are building blocks of a digital twin system, they cannot on their own provide the desired functionalities of a digital twin system.

The key characteristics and components of digital twins are collated in Table 1, with Table 2 then providing an overview of the differences between digital twins and a number of technologies relevant to them (from Sharma et al., 2022).

Table 1 Digital twins – key characteristics and components

Seamless integration between the cyber and physical spaces	Digital twins rely on data from multiple sources to create an accurate representation. This data can come from sensors, cameras, various IoT devices or historical records. The data can also be sent back through devices with actuator capabilities to execute commands in the physical entity.
Multiple data sources	The data fed into a digital twin should come from different sources. Although this increases the complexity of the system and requires higher computing capacity, it primarily serves to increase the

	accuracy and consistency of the data. It also promotes system resiliency in the event that a data source is unable to stream the information.
Seamless connection	Both the physical and the digital twins must be equipped with networking devices to guarantee a seamless connection and a continuous data exchange ether through various communication protocols (5G, LPWAN, satellite).
Real-time updates	Digital twins continuously receive dynamic physical twin data. The models are typically updated in real time or near-real time, reflecting changes and events happening in the physical world.
Remote monitoring and control	Digital twins enable remote monitoring and control of physical assets, which is particularly useful for complex systems or systems in remote or hazardous locations. A digital twin system can send data or commands back to its physical twin, to the domain experts, and to other digital twins in the environment, as well as predictions and prescriptions for system maintenance and for functional optimisations.
Closed-loop optimisation	The data between the cyber and physical worlds can be continuously exchanged to continuously optimise the physical side. Important: this feature is not possible in every use case (e.g., a digital twin of an aircraft).
Data storage	Data generated can be offloaded and stored in the cloud and/or at the edge, and can be retrieved at a later point or made accessible to other users (e.g., a system operator) and/or other digital twins. Also known as 'data lake', it is a centralised repository that allows structured or unstructured data at any scale to be stored.
Visualisation	A visualisation layer is a necessary element of a digital twin architecture. Together with user interfaces, it is essential for the usability of the digital twin, and it allows the user to interact with the system and take actions based on the data presented in a visual form (e.g., 2D or 3D maps).
AI, machine learning	AI integration becomes inevitable in the rapid evolution of digital twining. The continuously **improving AI**, supervised/unsupervised **learning algorithms** allow for identifying nonlinear data correlations and predictive capability of a digital twin.
Sources	(Barricelli et al., 2019; Sharma et al., 2022; Wang et al., 2022)

Table 2 How technologies differ from digital twins

Technology	**How it differs from digital twins**
Simulation	No real-time twinning
Machine learning	No twinning
Digital prototype	No IoT components necessarily
Optimisation	No simulation and real-time tests
Autonomous systems	Not self-learning (i.e., learning from its past outcomes) necessarily
Agent-based modelling	No real-time twinning
Source	(Sharma et al., 2022)

In short, a digital twin is more than a simple model or simulation; rather, it is an intelligent and evolving model – the virtual counterpart of a physical entity or process. The digital twin can follow the lifecycle of its physical twin to monitor, control and optimise its processes and functions.

2.2. Enabling technologies

The digital twin is not an emerging technology per se. The maturing of digital twins in recent years is a consequence of significant technological advances that have improved the capture, analysis, processing and visualisation of large amounts of data. Digital twins are based on a variety of underlying technologies that are only now reaching the point where they can be deployed reliably, cost-effectively and at scale (Table 3).

This means that digital twinning, in practice, is a multi-disciplinary field that involves a knowledge of computing science, automation, engineering, communication and operational management, not to mention expertise in all the application fields in which digital twins are being tested and deployed.

Table 3 Enabling technologies

Technology	**Description**
IoT and industrial IoT	The rapid growth of IoT is one of the main drivers for the adoption of digital twins. IoT devices form the base layer of a digital twin that enables data streaming in (near) real time. This area includes sensors (e.g., temperature, pressure, CO2) and devices such as smart locks, smart thermostats, smart actuators and smart cameras with machine vision. The choice of devices is almost limitless, and they are able to transmit data to the network via various communication protocols (LPWAN, WiFi, satellite). The increasing availability of hardware in terms of pricing, as well as capabilities and capacities (e.g., intelligent sensors), enables a completely new level of automation and process monitoring.
Cloud/ edge computing	The development, maintenance and use of digital twins is a computing- and storage-intensive undertaking. The cloud has made data storage scalable and cost-effective, but most importantly, it is accessible from servers over the Internet. Edge computing, which is now taking off commercially, is the better approach to many IoT applications (e.g., autonomous vehicles) that require low latency, rapid analysis (real-time decisions) and fast action, and cannot be processed in the cloud. Edge computing addresses the limitations of centralised computing by moving the processing closer to the source of data generation, ‘things’ and users. This decentralised architecture model represents a necessity to avoid unnecessary communication, minimise latency issues and reduce high data storage costs.
Hybrid connectivity	A resilient and reliable connectivity network is the backbone of digital twin operations, with the ability for ubiquitous connectivity being a critical factor. 5G technology enables mobile communication that supports a massive number of devices with a diverse range of speed, bandwidth and quality of service. 5G connects more IoT devices at higher speeds and enables various IoT scenarios – e.g., real-time road traffic monitoring, real-time management – and automates the smart electricity grid, public surveillance and security systems. Improving satellite communication, e.g., over Non-Geostationary Satellite Orbit (NGSO), represents a serious alternative method to provide broadband connectivity, especially for rural, remote or maritime areas. IoT services provided by networks of satellites will only keep growing. As an alternative to cellular or LPWAN, satellite IoT is particularly good for use cases like monitoring energy pipelines and infrastructure assets or delivering agriculture or aquaculture operations.
Advanced analytical tools	Advanced analytical tools, such as AI and machine learning, are critical for the usability of digital twins, and modern advanced analytics enable the generation of new insights from big and complex data sets. Trained on large amounts of data (historical and real-time), AI models provide digital twin systems with unique functionalities such as prediction capabilities for

	preventive maintenance, or autonomous decision-making in self-driving vehicles.
Virtual/augmented reality	The visualisation step is crucial in making a digital twin accessible to users. Insights generated from digital twins must be rendered either on a screen (2D) or in physical space (3D). Most visualisations for digital twins operate in 2D space, but increasingly, augmented and virtual reality enable the display of digital content in 3D. These tools create entirely new environments to render digital twins in a highly immersive way, creating the richest consumption of and interaction with the information.
Sources	(Attaran & Celik, 2023; Perno et al., 2022; Qi et al., 2021; Rasheed et al., 2020)

2.3. The IoT layer in a digital twin architecture

2.3.1. Digital twin architecture

Grieves and Vickers (2017) explained that a digital twin model "consisted of two systems, the physical system that has always existed and a new virtual system that contained all of the information about the physical system. This meant that there was a mirroring or twinning of systems between what existed in real space to what existed in virtual space and vice versa." This is the core premise of a digital twin and from it a very basic concept for a digital twin architecture can be derived.

The Industrial Internet Consortium (IIC) (2020) defined three major instances of a digital twin (see Figure 1): data, model and service.

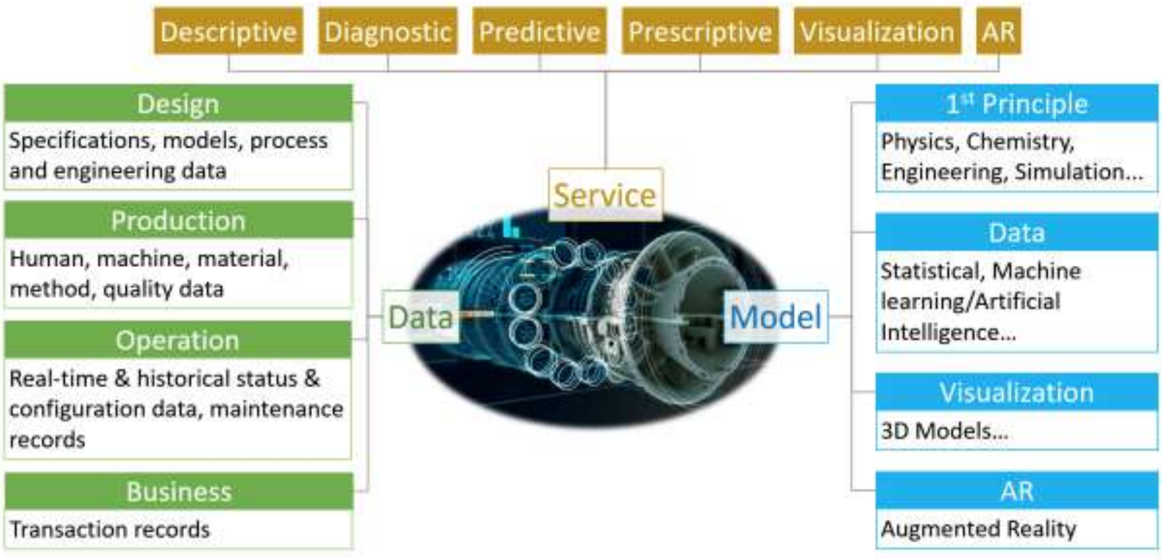

Figure 1 The constituents of a digital twin by Industrial Internet Consortium (IIC, 2020)

- Data: a digital twin represents its real-world twin through data on the states and behaviours of the real-world twin. Data gathered can include, e.g., design models, specifications, production processes, production equipment, materials and parts, production methods, quality assurance data, real-time and historical state, maintenance records, transaction records.
- Models: a digital twin should contain computational or analytic models that are required to describe, understand and predict the twin's operational states and behaviours. These models may include simulation models, machine learning and AI, 3D models and augmented reality.

- Service (interface): a digital twin contains a set of service interfaces for industrial applications or other digital twins to access its data and models. The service interface makes the digital twin accessible and usable (IIC, 2020).

Wang et al. (2022) defined a digital twin architecture for connected vehicles in three layers (see Figure 2):

1. the physical space where human beings, vehicles, and traffic infrastructures reside
2. the digital space where the digital replicas of those physical entities are located
3. the communication plane, which plays a crucial role in this framework to allow real-time and non-real-time data streaming for both upstream and downstream

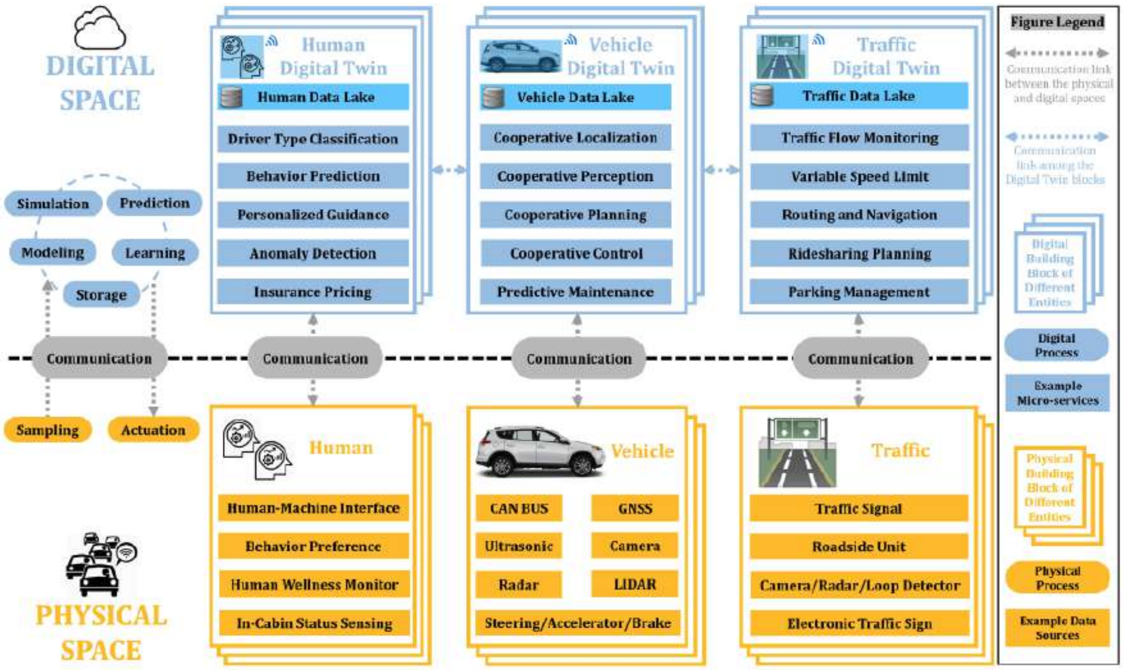

Figure 2 Digital Twin Architecture for transport (Wang et al., 2022)

The digital or cyber space can be viewed as the operational level of a digital twin, i.e., with the critical computing capabilities of the digital twin: visualisation, simulation, prediction, data exchange with third parties. This layer decides and sends commands to the physical space to initiate changes of status or behaviour.

Depending on the application scenario and intended uses of a digital twin, the physical and digital layers differ in terms of the input sources, amount of data generated, data management system, processing required at the digital layer, communication protocols and visualisation equipment. However, the conceptual framework remains unchanged.

The foundation elements of a digital twin infrastructure are data collection (e.g., sensors, documentation), data communication (e.g., API, protocols) and data computing (e.g., analytics, visualisation). The physical layer must communicate with the digital layer, either as a bilateral relation to actively manage the assets, or an open-loop digital twin to monitor the conditions of static assets (Kovacs & Mori, 2023; Li et al., 2022).

2.3.2. IoT architecture

IoT, as a critical enabler of digital twins, allows the dynamic state of the physical assets to be captured. Without IoT technologies, many use cases – e.g., traffic flow monitoring, use of parking spaces, condition monitoring of aircrafts, safety monitoring, smart packaging, asset tracking – would not be possible. Hence, connected devices, such as sensors, are a 'must-have' in a digital twin set-up.

Together with data transmission technologies, they guarantee that a digital twin can realise real-time data collection and synchronisation.

There are some similarities between the digital twin and IoT architecture, which can be summarised in three basic layers: data generation by connected devices, communication infrastructure and data analysis (either in the cloud or at the edge).

At CENSIS, IoT infrastructure is viewed in the form of a stack, as shown in

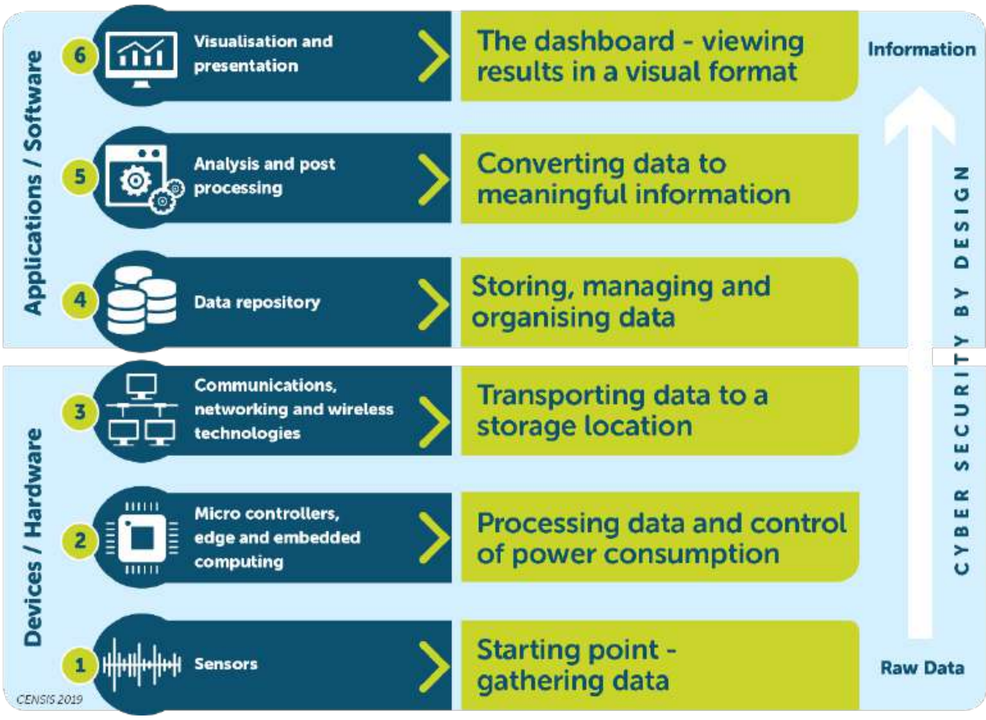

Figure 33.

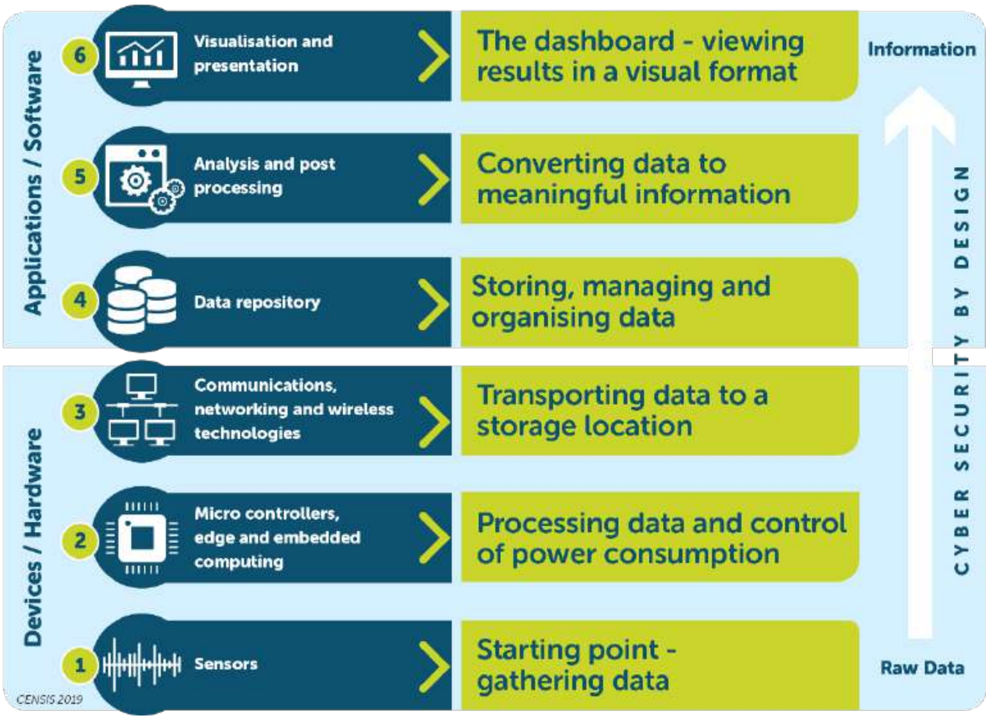

Figure 3 CENSIS IoT Stack

The CENSIS stack covers all components/layers of an IoT infrastructure (with cybersecurity measures in place throughout the whole stack) that form a complete package to unlock the full potential of the technology. A brief overview of the stack shows the key actions on each layer:

- As the data gatherers, sensors are the starting point of any IoT solution. As the types of sensors available expand, an ever-increasing variety of data can be collected. Whatever variable is measured, the sensor must record an accurate representation of the conditions. The better the quality of data gathered through connected devices, the better the value and insights that will result from the analysis.
- A microcontroller is an integrated chip that contains a processor (CPU), memory and interfaces to communicate with sensors. A processor acts as the brain of the IoT device. Depending on the application, this can simply read data and pass it to the communication module, or it can perform more powerful edge processing tasks.
- Connectivity and networking describe the wireless technologies used to transfer information from the sensors/end nodes to the cloud. There is a wide range of connectivity protocols and hardware solutions, each with its own strengths and weaknesses. It is worth noting that the communications module will usually have the highest power consumption out of all the system components in an IoT device when sending/receiving data.
- The edge IoT nodes of a network are limited in storage size and processing constraints. In an IoT application, thousands of nodes can collect data which is then moved on to database storage either locally hosted or on a cloud storage platform where it can be processed from a centralised location.
- Cloud computing can break up the limitations of local computing devices whilst improving the overall computing capacity. Hence, IoT data is usually processed on the cloud. Its huge processing power enables the execution of complex algorithms, machine learning and AI to extract maximum value from the data**. Analysis of the data is where the real value is unlocked and many IoT companies build their value proposition around this.**
- The final stage of the process is to present the information in a meaningful way. Depending on the requirements of the user, this could be as simple as sending an alert by SMS when an abnormality in the process occurs. More frequently, it is a web page or dashboard, with graphs showing real-time information from the network. Many cloud platforms include tools to visualise data, and businesses such as Amazon Web Services (AWS), Alibaba Cloud and Microsoft Azure provide complete IoT suites for IoT and SAP cloud platforms as well as for handling big data. This layer may also include an automated feedback loop or manual two-way communication.

2.4. Using IoT to support the decarbonisation agenda

2.4.1. Decarbonisation and GHG reduction

Decarbonisation focuses on reducing CO2 emissions resulting from human activity, with an eventual goal of eliminating them. It can also be viewed as decreasing CO2 output per unit of energy generated. The 2015 Paris Agreement set a goal to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. To limit global warming to 1.5°C, greenhouse gas (GHG[1]) emissions (including CO2) must peak before 2025 at the latest and decline by 43% by 2030 (UN, n.d.).

In practice, this requires a shift from fossil fuels toward alternative low-carbon emission energy sources. Decarbonisation will therefore require a fundamentally different energy system that will

[1] Greenhouse gas emissions are measured in million tonnes CO2 equivalent (Mt CO2e). Source: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport (retrieved 18/10/2023)

change all sectors through the use of alternative energy sources based on green electricity and green molecules (such as biofuels and hydrogen) (Deloitte, 2023).

As the focus of this report is transportation, we should consider how the system contributes to GHG emissions. The answer, unfortunately, is that it contributes significantly. As reported by the European Environment Agency (2023), the exhaust emissions of transport (including aviation bunkers) were responsible for 25.9% of total GHG emissions in the EU-27 in 2019, with CO2 emissions accounting for 98.8% of the exhaust GHG emissions from transport. Within the whole sector (including airplanes and vessels), car transport accounted for 43.9% of GHG emissions in 2019. According to preliminary estimates, emissions increased by 7.7% in 2021, due to a recovery effect in the economy. On the bright side, research by the European Energy Agency found that, even with electricity generation, the carbon emissions of an electric car are around 17–30% lower than driving a petrol or diesel car. While contributing to the decarbonisation of road transport, the electrification of the road vehicle fleet will significantly increase the demand for electricity. The impact assessment of the CO2 emission performance standards of cars and vans indicates that, with a high penetration of electric vehicles (EVs), their electricity consumption could reach around 11% of total electricity consumption in 2040, compared to a share much below 1% in 2020 (EEA, 2023).

As reported by [Our World in Data (2020) (Figure 4)](), in terms of transport modes, 74% of global transport emissions come from road vehicles.

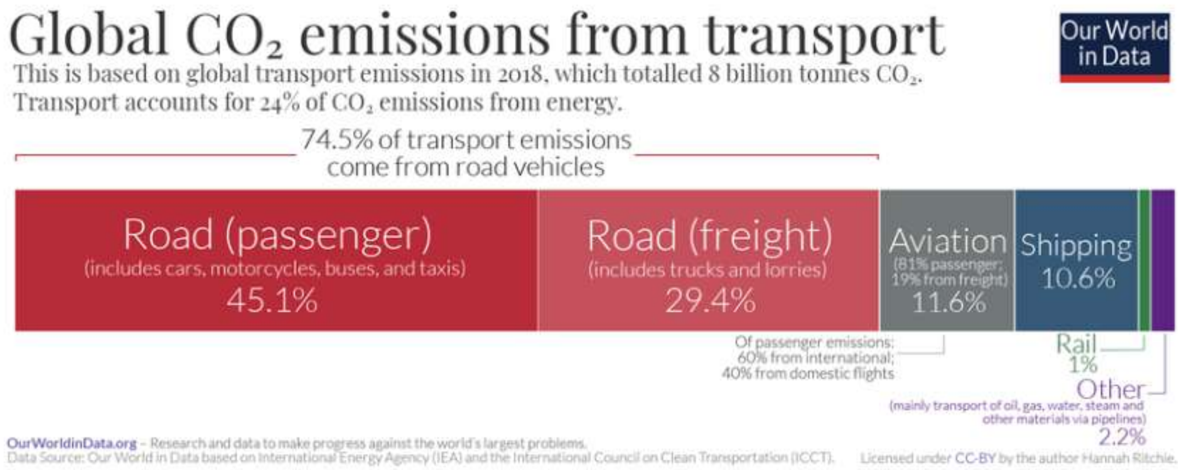

Figure 4 Global CO2 emissions from transport
Source: https://ourworldindata.org/co2-emissions-from-transport (retrieved 03/10/2023)

One of the more difficult industries to address in any decarbonisation discussions or planning, is shipping, considered to be the backbone of the global economy and accounting for around 80% of the volume of global trade in goods, according to UNCTAD (2023). As the industry continues to grow, it generates increasing carbon emissions (Deloitte), and the International Maritime Organization (IMO) has set an ambition to reduce international shipping carbon emissions per transport work (ton-mile) by at least 40% by 2030, and 70% by 2050. The 2023 IMO GHG Strategy also includes a new level of ambition relating to the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources which are to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030.

As different transportation sectors, subsectors and parties consider their own decarbonisation pathways and requirements, it is important to consider and understand the role that IoT systems can play in this.

2.4.2. The role of IoT in decarbonisation

IoT systems contribute to decarbonisation through data generation and overall 'digitisation' of things. As such, IoT solutions are industry-agnostic and offer similar functionality across industries, enabling new insights through data, system monitoring and automation. Networks of intelligent sensors, combined with real-time analytics, can drive significant improvements in manufacturing processes and operational efficiency, reducing waste, minimising unnecessary resource consumption.

Below we highlight and summarise just some of the ways in which IoT can support decarbonisation efforts and unlock the benefits of new technologies:

- IoT has the potential to transition energy grids to renewable energy such as wind and solar energy through intelligent metering and forecasting. It can enable the integration of renewable energy sources by providing real-time data on energy production and consumption – information that can be used to help balance supply and demand more efficiently. With more EVs on the road, it is important that IoT-enabled EV charging stations can optimise charging based on grid demand and renewable energy availability. By providing granular information and ensuring greater transparency on distributed energy resources, IoT technologies can be used to better inform stakeholders and shape energy efficiency policies.
- IoT systems provide reliable emissions measurements and data for evaluating and verifying carbon offset plans. Similarly, IoT monitoring and automation systems in carbon capture projects improve the accuracy, reliability and scalability of such endeavours. A good example is CarbFix (Iceland), where various sensors (temperature, pressure, gas detectors) monitor the physical state of the CO2 transported within a defined process or system, and a process-flow analyser monitors the chemical composition of the gas delivered to the injection system. Installations are closely examined with CO2 sensors placed to detect any leaks. The IoT system in place is complementary to the deployed CO2 capture technical solution (injection and mineralisation) and ensures safety of the premises and accuracy of the technical solutions.
- Various (IoT-enabled) smart building solutions ensure more energy-efficient building management. This can be as simple as turning off lights in unoccupied rooms, closing the security door in case of fire danger, or regulating heating or air conditioning in large buildings by tracking occupancy. All these seemingly simple and conceptually straightforward solutions are feasible thanks to IoT technologies and can visibly improve the energy efficiency of a building.
- In fleet management, IoT devices can help optimise routes, monitor vehicle performance and promote eco-friendly driving practices, reducing fuel consumption and emissions. An excellent example is truck platooning, which is a way of combining many vehicles into a convoy using connective technologies and automated driving technologies. With the vehicles moving in convoy, drag is reduced which in turn reduces fuel consumption and CO2 emissions. The orchestration of the convoy requires multiple technologies including vehicle-to-vehicle (V2V) communication, cloud communication and automated driving, and Volvo, Scania and DB Schenker are among many businesses working on this solution. Other examples of IoT deployment in fleet management include sensors for fuel monitoring, allowing fleet managers to detect fuel inefficiencies. Data can then be used to optimise routes and reduce fuel costs. IoT also plays a role in vehicle maintenance and diagnostics (assets management), where proactive maintenance helps to prevent breakdowns and extend the lifespan of vehicles.

It is important to emphasise that while CENSIS promotes the measurable advantages of IoT systems, it also recognises that the IoT sector has its own carbon footprint. The ICT sector as a whole accounts for approximately 7% of global electricity consumption and this is forecast to rise to 13% by 2030 (EU Commission). The negative environmental effects of ICT include the use of non-renewable and environmentally damaging resources, e.g., lead and mercury, and pollution caused by the disposal of e-waste (both electronic and electric). The ever-increasing handling of computing tasks and storage capacities via the cloud or high-performance computers has resulted in data centres becoming a key infrastructure element of ICT systems, with data centre energy consumption in the EU expected to increase by over 200% between 2020 and 2030. Hence, there is a strong push in the IoT world towards sustainable solutions, including green, low-energy storage, reusability and repurposing.

Against this backdrop, it is important to approach IoT use consciously and to look beyond the standard narrative of the benefits of IoT systems. With large IoT systems particularly, it is advisable to carefully examine the cost-benefit ratio of IoT use, which goes beyond the classic economic calculation. The latest report of the AIOTI (Alliance for the Internet of Things Innovation) on "IoT and Edge Computing Carbon Footprint Measurement Methodology" (September 2023) provides guidance on methodologies for measuring ICT carbon footprint, and includes a method for calculating the avoided carbon emissions in an industrial sector/domain when ICT is used as an enabling technology.

2.5. IoT in intelligent transport systems

IoT solutions have secured a permanent place in modern transportation systems, with the integration of IoT systems with the transport infrastructure enabling better and safer travel, environmental sustainability and economic development. IoT devices (e.g., sensors, RFID tags and readers or positioning systems) can collect information about traffic conditions in the environment where they are placed, including road conditions, traffic accidents, or road repairs. This information can be used to inform intelligent decision-making such as the timings of dynamic traffic lights or changing the number of lanes available in each direction (Guerrero-Ibanez et al., 2015). IoT-enabled smart transportation solutions have been utilised and deployed by multiple stakeholders, and some public authorities are already implementing roadside infrastructure such as cameras and sensors to collect data on environmental and traffic conditions. Auto-makers are developing new in-vehicle sensors to promote V2V and vehicle-to-infrastructure (V2I) communications (Guerrero-Ibáñez et al., 2018).

CENSIS itself has already helped a number of organisations to start their transport related IoT-journey, enabling new capabilities to improve their operations:

- **FUELlink Systems**, a Lanarkshire-based fuel management company, launched a new product called VINIE at Euro Bus Expo 2016 in Birmingham in November 2016. Developed with assistance from CENSIS, VINIE uses Bluetooth technology to automatically check vehicles' identification, allowing buses, vans, cars, and trucks to be refuelled more quickly and securely. Combined with FUELlink's fuel management system, the product can accurately check odometer readings, required by bus companies for rebate claims, and use this data to calculate miles driven per gallon, which in turn, can be used to detect fuel tank leaks or to benchmark efficiency. The device can also include the vehicle's fuel tank level at the point of fuelling, providing valuable information for fleet operators.
- With support from CENSIS, **East Renfrewshire Council** was one of the first local authorities in Scotland to use IoT to deploy a 'smart gritting' system, integrating the existing weather data used when deploying gritters and further improving safety for road users. In Autumn 2020, robust, low-cost sensors were installed on roads on the outskirts of Barrhead – an area prone to low surface temperatures – to measure the temperature of the road. The data can then be viewed by the Council, using an IoT network, and utilised in tandem with weather data to target resources in areas most in need. Already, the sensors have been used over and above specialist weather forecast information to better inform and change gritting priorities in real time to improve public safety.
- CENSIS supported a Scottish start-up, **DigiFlec,** to develop an IoT sensor network that provides real-time monitoring of rural road conditions. DigiFlec worked with Forestry and Land Scotland (FLS) to develop a digital transport network management interface. The initiative combined the digital mapping of the road network alongside IoT-enabled sensors deployed to capture live data about the condition of the FLS road network. The data included readings on temperature, moisture

in the road, and potential culvert blockages, and was integrated into a digital interface that displayed the data in real time, as well as any long-term changes to a road's condition. This has enabled better maintenance scheduling and, ultimately, provided greater knowledge of the factors that impact a road's deterioration, allowing decisions to be made to prevent excessive damage and better allocate resources for repair and upgrade work.

Also, in Scotland a Heriot-Watt University spin-out, **MicroSense Technologies Ltd**, developed a state-of-the-art sensing system to ensure an equal spread of grit across road surfaces. Measuring around the size of the average mobile phone, the device can be fitted to a gritter and uses advanced data analysis and bespoke radar sensing to detect how much de-icer salt is already on the road. This information is instantly fed back to an on-board computer, allowing the vehicle to automatically adjust the amounts of grit required, whilst also recording the condition of the road surface. Data will be added to a mapping programme that will identify the roads most impacted by ice and frost. It will also inform a predictive model that will improve road safety and minimise travel disruption (HWU, 2019).

Elsewhere in the world, an IoT system was deployed as part of a digital twin to monitor diverse parameters in the underground excavation of a subway station, Shikui Road Station of Dalian Metro Line 5 in China, where engineers deployed an IoT system and a digital twin to offer a novel approach in construction of subway stations. The IoT sensors were arranged to collect the most critical information in tunnel monitoring, such as top arch settlement, surrounding rock deformation and steel arch structural stress. The developed 'smart' system can be used to monitor and plan the construction process of the arch cover method station, which is essential to ensure construction safety management. The developed model enables the dynamic (real-time) adjustment of the construction plan (Jiang & Jiang, 2022).

Another important application of IoT technologies is in new-generation bike-sharing systems. Unlike in traditional bike rental systems, these new non-docked mobile bike-sharing services allow the automatic renting and returning of bikes. These share-bikes are equipped with smart locks and GPS for precise positioning systems and use IoT to collect a large variety of data from different dynamic sources. The data generated is used not only to help users find a bike, but also to allow city officials and planners to understand behaviour patterns, adapt to demand and make infrastructure changes for sustainable urban planning. The Helsinki bike-sharing system – generally considered to be the most advanced system in operation – runs on an AI platform that allows the scheme to be optimised to reduce operational costs and make the sharing scheme more widely available in the city (IoTNOW, 2018).

2.6. Conclusion

Simply put, the concept of the digital twin, which emerged from the testing of aerospace systems, describes the representation of real-world assets in the digital world. In this way, not only can products and machines be 'twinned' or production facilities mapped with digital twins but in the future digital twinning could also be used for entire cities including the processes and digital services offered or across a whole logistics supply chain. It is also irrelevant whether the physical counterpart already exists in the real world or will exist in the future (e.g., product design). Digital twins merge reality and virtuality, create transparency in complex technical and operational processes, and represent an indispensable tool for the development and operation of cyber-physical systems (CPS). They can support businesses across their value chain by providing clarity through digital data.

The potential of digital twins in various applications is immense, and IoT technology is a fundamental enabler of this potential across various industries. The real-time data, monitoring, and connectivity provided by IoT enhances the accuracy, usefulness and capabilities of digital twins, giving them the capabilities they are promoted for. Connected devices, like sensors, are a 'must-have' in a digital twin set-up. Together with data transmission technologies, they guarantee that a digital twin can realise real-time data collection and synchronisation.

When it comes to the decarbonisation agenda, IoT solutions are industry-agnostic and facilitate data collection and processing to gather new insights across sectors. These data-backed insights, whether on energy or fuel consumption, resource management or pedestrians' behaviour, can lead to actions like better urban green planning, new environmental policies, greater availability of bike sharing, more fuel-efficient fleet management, and much more.

At CENSIS, we regard digital twin technology with its predictive capabilities as an advanced stage of an IoT evolution. To use an old but ever-relevant saying, information is power. IoT infrastructure empowers a digital twin with the information (data) that is later organised, processed and made available to users and relevant stakeholders who can translate into benefits and improvements.

With increasing electrification, automation and diversification of transport methods (both people and goods), the interactions between diverse elements of transport infrastructure become increasingly complex. This requires the integration of various data analytics tools and data-gathering IoT infrastructure, e.g., to understand the impact of autonomous vehicles throughout traffic flow, energy demand for EV charging, response to road closures and prioritisation for emergency vehicles, and planning of the fleet routes in logistics. In this respect, the use of digital twins now appears to be a prerequisite for the advanced digitisation of the transport sector.

3. WP2 Transport digital twins and decarbonisation

Transportation is one of the pillars of modern economies and includes the mobility of people and goods. Modes of transport are characterised by an inherent complexity: several elements influence each other directly or indirectly, and in a very dynamic way. Technology changes lead to new levels of interaction between system elements and their users and enable a variety of new services in freight transport or personal mobility.

Furthermore, transport is affected by societal changes resulting from economic and geopolitical vulnerabilities such as economic crises, limited natural resources, political instability and, recently, the Covid-19 pandemic. Across the world, decarbonisation pressures (both political and social) are already transforming transport, including the way it is organised, managed and made accessible.

Among the many possible applications of digital twins, combining them with decarbonisation efforts can be highly effective in achieving sustainable and environmentally-friendly transportation systems. Although digital twins have clear potential to optimise the transport sector in a variety of ways, their use in industry is still at an early stage. As the previous chapter touched upon, digital twins of individual assets or components can be used to test and develop products, track functions (e.g., vehicle health) and predict maintenance needs. With the help of digital twins of larger ecosystems, transport and infrastructure, traffic and logistics management or intelligent driver assistance can be monitored. New digital twin technology in transport has expanded beyond traffic congestion and flow analysis and signal optimisation to autonomous vehicle training algorithms, transportation infrastructure planning and management, and the operation of transportation systems and mobility services.

This chapter goes beyond the definitions and introduction provided in the chapter on IoT-enablement in transport digital twins, and investigates in more detail a number of matters related to the implementation of digital twin solutions in transportation, starting with the benefits from the technology. It begins by seeking to answer the question of how to create a value from digital twin implementation and makes suggestions for what should be considered in the design phase of a digital twin system. It also provides estimates, sourced online, of the costs of a digital twin solution and enlists variables that go into the final calculation. The final sections of the chapter then consider the environmental aspects of digital twins: first from the point of view of the decarbonisation impact of digital twin implementation, and secondly from the point of view of building green digital twin systems.

Unfortunately, like all ICT-based solutions, digital twins are part of the carbon footprint story, and the impact of their use should be taken into consideration, just as with any other intensively computational ICT-based product.

3.1. Benefits from digital twins in transportation

In 2018, at the panel discussion in Morgan Stanley Laguna Conference in California, Dennis Muilenburg, CEO of Boeing, said that the company's use of digital twins in the production of components had increased the quality of parts and systems used in aircraft production by 40%. Complementing this statement are various studies that emphasise the increasing role of the digital twin in monitoring aircraft health. It is also estimated that digital twinning can support maintenance, and improve cycle time for critical processes by 30%; additionally, evidence suggests that engineers can use a digital twin to determine with greater accuracy the lifespan of aircraft structural components (Ibrion et al., 2019).

As those examples from the aerospace sector demonstrate, digital twins, when successfully deployed, can offer a myriad of benefits, including helping to improve performance and decision-making, generate savings and increase operational flexibility.

Moving from aerospace to the built environment, smart cities are at the forefront of digital twin applications and this is intensively discussed in the literature. Figure 1 shows how digital twins work in the context of the smart city application. Ideally, the digital twin for a smart city could simulate the entire urban system to coordinate and manage the city as a whole, centralising urban information for integrated urban management while maintaining some decentralised autonomy for each urban subsystem (Li et al., 2022).

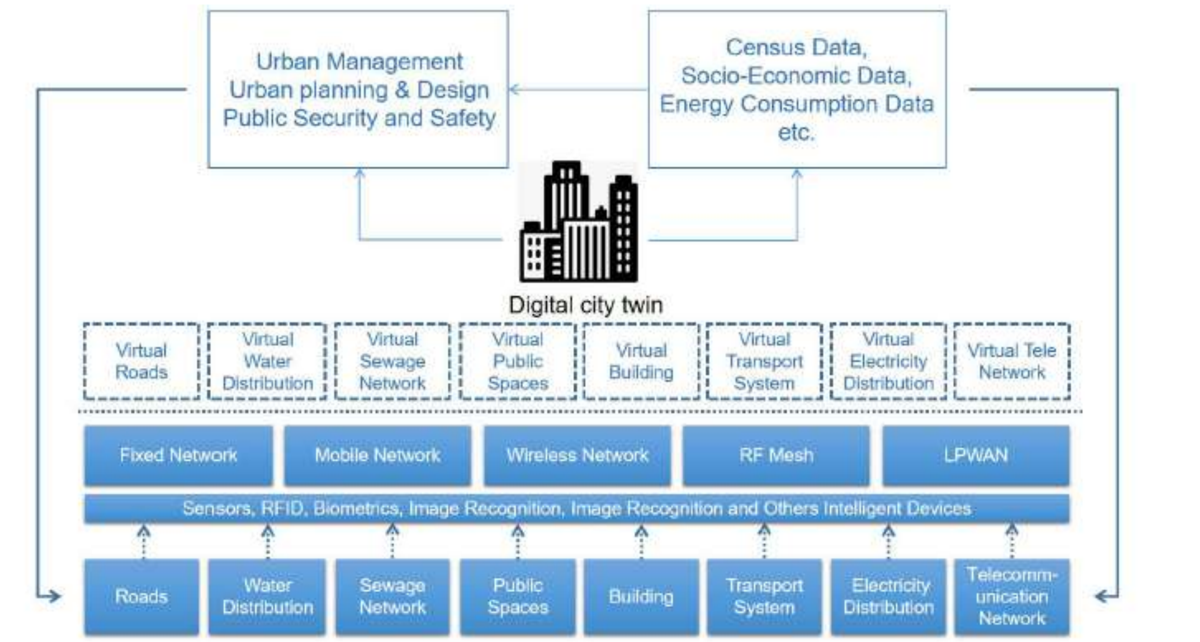

Figure 5 Smart cities applications (Li et al., 2022)

IoT Analytics, in a report on the Digital twin market 2023-2027, analysed 100 digital twin projects from several market sectors, and defined three dimensions of digital twinning:

- the lifecycle phase of the physical assets (from design to decommission)
- the hierarchical levels (what is being ‘twinned – a whole system, a product, a process?)
- the most common uses of a digital twin (monitoring, prediction, visualisation).

Based on those categories, IoT Analytics identified 210 potential different digital twin combinations, and thereby provided an interesting summary of the most common uses for digital twin systems. Figure 6 illustrates IoT Analytics’ 3D representation of its classification approach; as the authors indicated, many digital twin initiatives cater for more than one combination (Hasan, 2023).

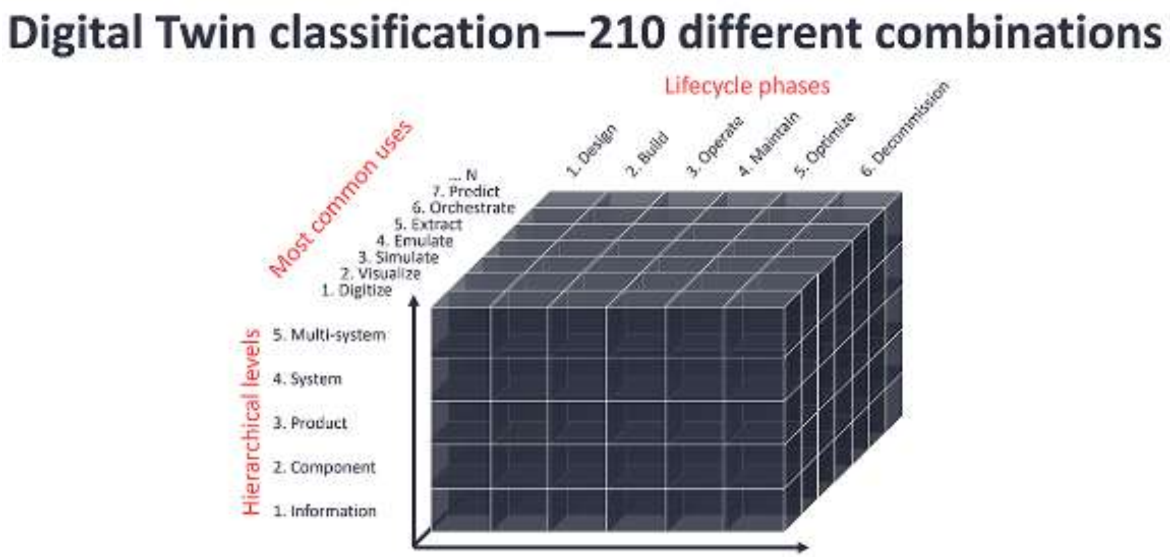

Figure 6 Digital twin uses – 210 combinations (Hasan, 2023)

	Digital twin application	Description	% of projects
1.	**Twins for system prediction**	A digital twin geared toward predicting complex systems	30%
2.	**Twins for system simulation**	A digital twin geared toward simulating complex system behavior	28%
3.	**Twins for asset interoperability**	A digital twin geared toward common data formats and streamlined data extraction in complex systems	24%
4.	**Twins for maintenance**	A digital twin geared toward assisting with maintenance-related use cases	21%
5.	**Twins for system visualization**	A digital twin geared toward visualizing a complex system (e.g., in 3D)	20%
6.	**Twins for product simulation**	A digital twin geared toward simulating the behavior of (future) products (mostly during the design phase)	9%

Figure 7 Digital twins most common uses (Hasan, 2023)

Table 4 provides a list of the benefits of digital twins with explanations of how they positively impact transportation systems and services.

Table 4 Benefits from digital twins for transport

Benefit	**Explanation**
Enhanced decision-making	Digital modelling allows for pattern analyses, and discovering hidden patterns in data coming from various sources. Valuable new insights facilitate planning and improve accuracy in decision-making processes. For example, urban digital twins can simulate and evaluate the effect of new city structures on urban mobility and transport to improve city planning. It can optimise the real-time urban mobility conditions by predicting future states. They can support advanced decision-making to align resources more efficiently for passenger and freight transport. Digital twin visualisation is an excellent way to present high-degree complexity by creating links between diverse sources of information and integrating predictive and scenario elements. This function can bridge the gap between data and its use in advanced decision-making.
Risk-free experimentation	A digital twin can be described as a virtual laboratory where engineers can disrupt the system, study its reaction and develop robust mitigation plans. They can test extreme conditions that cannot be physically performed. In this way, digital twinning makes it possible to run 'what if' scenarios and test probabilities, running simulations for seamless implementation. Using historical data can minimise the risks associated with untested ideas. In an urban mobility context, city planners can simulate different urban development scenarios and their impact on various outcomes such as noise, environment and citizen well-being. Digital tools such as metaverses and extended reality could provide an experimental playground to try out alternative organisations of cities and societies.
Real-time risk management	Digital twins can enable people to identify potential emergencies and develop strategies to overcome them, or to anticipate and address vulnerabilities before they escalate. The visualisation capabilities help to illustrate the impact of taking risks, and assess potential outcomes. The development of new products or services is accelerated since digital twins make it possible to test and fine-tune details in the digital realm, saving time and resources.
Improved asset management	Real-time data streaming provides precise insights into asset performance and status. Simulation, forecasting and virtualisation tools can also support and advance the design of transport assets for maximised service life, taking into account circular economy and ecological footprint issues. Digital twins can provide stakeholders and service providers with actionable information to analyse data and control vehicles securely from the cloud.
Optimised fleet management	Digital twins are useful for improving route planning across the fleet by taking into account the required regulatory compliance and weighing the trade-offs between faster routes

	by air and cost-effective options by ship. The advanced analytics can uncover bottlenecks and disruptions and reveal routes that may have been missed. Improved route optimisation and dispatch planning results in cost savings, including savings from reduced fuel consumption.
Product/service design	Within transport manufacturing, digital twins enable resource-friendly product development and testing as it can be done digitally. Based on user feedback and improved data collection of requirements, product usage and user preferences, digital twins can enable a better alignment of products to user needs. This is particularly relevant in the context of an expected increase in demand for customised products and services.
Predictive maintenance	Digital twins enable proactive measures before failures occur. They can anticipate faulty scenarios, analyse maintenance workflows and test various fault scenarios. In logistics, the value of predictive maintenance goes beyond cost savings and operational efficiency. It helps improve asset performance, prolong equipment lifespan and reduce downtime.
Reduced environmental impact and improved sustainability	Digital twins can play a crucial role in waste reduction and energy efficiency. They can optimise transport by analysing a range of information, such as user behaviour and local traffic flow patterns. By identifying inefficiencies, they can be used to find more energy-efficient approaches, including reducing the carbon footprint of different transport systems by optimising the overall process.
Sources	(Attaran & Celik, 2023; Burak, 2023; Dohrmann et al., n.d.; Hasan, 2023; Muench et al., 2022; Rasheed et al., 2020)

Because the benefits of digital twins are based on a network effect, the value creation of twinning increases with the number of participants. In order to achieve this, standardisation and interoperability is needed on various levels, such as hardware integration, data integration and processing.

3.1.1. Practical examples

- **System simulation**

In 2011, DB placed an order with Siemens for 170 new high-speed trains, with the deal worth around €5.3 billion. For these trains (known at the time as 'IC' trains but renamed 'ICE4' by DB in 2015), Siemens developed a new car-based train control architecture that had not been deployed before. To reduce development costs, Siemens created a digital twin that would simulate the entire train's functionality of 40 different subsystems; the main feature of the solution was a functional simulation that used a representation of the electrical schema of the train in the simulated environment. Siemens estimates the digital twin-based simulation reduced cost by $1 million to $8 million (Fender, 2017; Hasan, 2023).

- **Maintenance**

German utility company E.ON embarked on a project that allowed it to shift to a more preventive, predictive and risk-based method of maintaining its assets. E.ON collaborated with DNV experts in energy systems and digital solutions and other partners such as SGB-SMIT, Maschinenfabrik Reinhausen and Westnetz, to create a digital twin that monitors asset health and performance of 110 kV power transformers. As part of the project, E.ON implemented a cloud-based digital twin that is used for better prediction of asset failures; this allows the company to evaluate failure modes per asset type and determine the remaining life of the equipment fleet (Hasan, 2023).

- **System visualisation**

The national railway operator of Italy, Ferrovie dello Stato, is working on a digital twin of the rail infrastructure that includes more than 10,000 miles of tracks, stations, tunnels, bridges, signals, switches, electrification hardware and the relevant IT systems that coordinate everything. Train cars carrying digital twin hardware have a yellow box on each end and arrays of sensors and lights that illuminate structures like bridges, tunnels, electrification equipment and station awnings. Each car is labelled 'Rail 3D Asset Digital Twin'.

Picture 1 Ferrovie digital twin yellow box
Source: https://www.ferrovie.info/index.php/it/17-approfondimenti/12378-ferrovie-rfi-il-modello-unico-infrastruttura-fisica-muif-col-rail-3d-video (retrieved 19/10/2023)

The first digital twins used by Ferrovie dello Stato sourced the data from sensors such as cameras and GPS receivers and employed advanced learning algorithms to create an interactive 3D replica of the rail system. ArcGIS was used for 3D visualisation of geographical elements, creating a complete visual inventory of the railway infrastructure. Nutanix software was used to operate a data system that processed and managed terabytes of information. The system was made compliant with the requirements of regulators and military authorities, which have stringent demands for security and data governance. The resulting digital twin now helps railway managers in the control room to visualise infrastructure such as bridges and stations remotely throughout the rail network. It also helps local staff prevent safety hazards and boost on-time performance (Hasan, 2023; Mangan, 2020).

3.2. The human factor

Digital twins are part of the ongoing digital transition that influences much of human activity in the developed world. One of the inherent challenges in this is the need to ensure the digital transition is a fair, inclusive and just process. This means protecting people who may be adversely affected by the necessary and sometimes paradigm shifts.

A perception of fairness and transparency is a significant factor in social acceptance of new technologies. For example, a successful digital transition requires that digital connectivity is accessible to all, regardless of location, income, education-level or age. A just transition also encompasses ethical concerns that touch on many aspects of the way in which digital twins would be applied or would need to work. For example, there are ethical concerns about the use of AI, such as a lack of transparency around how AI creates its output and the sources of data it uses, its capacity to replicate biases, or whether it can be held accountable for decisions made to support the public sector.

Some of the ethical concerns linked to transportation connect strongly with the just transition narrative, and there are trends in the transport sector that may point to fundamental changes in user behaviour, influenced by new technologies and politics. Growing consumer awareness of the environmental impact of transport is generating a bottom-up shift away from *owning* a means of transport towards using it as a service. This in turn exposes areas of unmet need in Mobility-as-a-Service, and how private, public and community can be brought together to create the just transition (Helbing & Sánchez-Vaquerizo, 2023; Muench et al., 2022). In any digital twin of urban mobility, incorporating human behaviour as a data model/source presents a unique challenge: the socio-economic context is constantly changing (often triggered by technological innovations), business models are evolving, new policies are being adopted, and new services shape consumer behaviour. The human factor has an almost embedded volatility that needs to be taken into account in the data modelling phase for any transport digital twin, in particular in urban logistics planning.

Researchers and businesses are already looking at these human factor issues. For example, researchers examined behavioural changes due to new services such as on-demand delivery methods (Deliveroo, Uber Eats and so on) and the growth of e-commerce, which led to an increase in on-demand personal motor vehicle trips in cities and urban freight transport (and therefore an increase of GHG emissions). Similarly, in retail and e-commerce applications, companies are developing increasingly sophisticated models of consumer behaviour. Data on past purchases, web browsing habits and social media activity is already being used by many companies to target advertising and promotions for specific customers and contexts. These models may evolve into consumer digital twins: complex, multi-attribute behavioural models that will attempt to predict future behaviours and proactively influence purchase decisions (Dohrmann et al.).

Researchers also propose the development of logistics 'living labs' to develop efficient and common solutions that are independent of previously adopted 'predict-and-provide' decision-making approaches and paradigms. Marcucci et al. concluded their research on planning in urban logistics stating that "without a sound theory and knowledge with respect to the relationships linking contextual reality and choice/behavior, it is not possible to make sense of what happens in the real world. Therefore, the joint use of behavioral and simulation models should characterize a DT [digital twin] within a Living Lab approach so as to simulate effective, well-informed and participated planning processes, but also to forecast both behavior and reactions to structural changes and policy measures implementations" (Botín-Sanabria et al., 2022; Marcucci et al., 2020)

Another dimension for a digital twin transformation is the organisational culture and how it adopts and accommodates innovations. Kuguolu et al. stated that improving understanding of the technology and promoting its organisational acceptance must occur at all levels in smart cities, including boardrooms, factory floors and everything in between. Their research found that establishing a culture that encourages innovation and enables precise alignment between departments appears to be a problematic but necessary step. It is essentially an example of the paradigm shift that digital twins must drive. This generally requires technology sponsors and change management experts who can embrace the technology and communicate the right messages across different levels within the organisation. Their findings support the view that investments in human capital and upskilling the existing workforce pay off: the lack of these investments increases the hurdles for initiatives (Kuguoglu et al., 2021).

Regarding skills availability, the European Union has investigated the impact of the twin transitions on employment and re-/upskilling demand, and the shortcomings in skills development and the lack of adequately trained workers are seen as the most important barrier to the uptake of digital technologies. In the EU, the green transition is predicted to lead to a net increase of up to 884,000 more jobs by 2030, but each economic sector will be impacted differently. While some sectors may lose jobs, many new technologies and methods require skills and labour that is not readily available in today's economy. Reskilling is therefore an essential factor to bring workers into new or changing sectors (Muench et al., 2022). Given the level of change management and skills development required for digital transformation, there is a need to introduce digital education for younger generations, and also upskilling and reskilling programmes. We need programmes and apprenticeships to promote digital, entrepreneurial and transversal skills.

3.3. Creating value from digital twins

3.3.1. Costs of digital twin development

The costs associated with implementing and maintaining digital twin systems can vary significantly depending on the complexity of the project, the industry and the specific goals of the digital twin, the amount of data to compute, the physical infrastructure to deploy, the maintenance of both physical and digital systems, and more. And the costs can represent a significant barrier to the adoption of digital twin solutions. From the case studies in the literature, the cost to implement a digital twin system can easily be US $1 million or more. Although there are clear quantifiable benefits from digital twin technology, these will not happen without the necessary upfront investment in the digital twin infrastructure. (McMahon, 2022)

RisingMax, a leading VR app development company, offers cost estimates for some parameters of a digital twin platform; these are shown in Table 5.

Table 5 Costs associated with developing a DT by RisingMax

Designing Cost Of Digital Twin	10k To 20k
Cost For Outsource Software	$35 To 65k
Cost Of Deployment	$15k
Cost Of Integration	$10k
Cost For Maintenance	$1500 To $4000
Cost For Hiring Project Manager	$25/ Hour
Quality Assurance Team And Testers	$5000

The numbers in Table 5 may seem affordable, but this summary estimate is far from comprehensive. RisingMax explains that the programming language represents a significant cost factor in development, which can quickly reach six-digit amounts. The user experience and features included in the digital twin platform, which make the platform more usable and successful, also contribute to higher development costs.

According to Visartech, an interactive software solutions company, the estimated costs of a basic asset digital twin with functionalities such as the exact 3D copy of an asset, a rotating module, animation capabilities, integration of the virtual twin into the system, and testing, rests between US $79,000 and $132,000.

It is also important to note that deploying a digital twin is not like purchasing and installing software. Rather, digital twins are products of an ecosystem that includes physical and virtual components that work together, usually in unique or highly bespoke ways. Not all ecosystems are healthy, and problematic environments do not function nearly as well as their less problematic counterparts. So what is the key to a successful digital twin in this context? It is data, particularly **data clarity**. Digital twins require information to function. If they cannot read properly and extract what they need, they will not deliver an acceptable return on investment (ROI), or at least nothing meaningful. Therefore, investing in accessible data infrastructure could be a substantial part of the upfront cost of deploying digital twins and should not be neglected (McMahon, 2022).

To sum up, these key considerations related to the costs of digital twins are as follows:

- Initial implementation costs include development of digital twin infrastructure, hardware, software, and integration into existing systems.
- Creating a high-accuracy digital twin, especially for complex systems, can be a significant upfront investment.
- Data collection and sensor infrastructure – the cost of sensors and their installation can vary greatly depending on the type and number of sensors required.
- There are costs arising from data processing, storage and computing power.
- Data visualisation and user interface costs mean that digital twin software development can be a significant expense, especially for a custom solution.
- Licence fees for commercial digital twin software (and related computational models) can also increase costs.
- Maintenance and updates will be required, including software updates, sensor maintenance and data cleansing. Failure to maintain the digital twin can result in inaccuracies and diminished value.
- There are costs involved in operating the systems, e.g., the entire infrastructure consumes energy.
- Security, such as encryption and access control, data protection, should also be considered in operating cost estimates.
- Hiring and/or retraining employees or bringing in experts, including change management support, can also add to the operating expenses.
- Integrating the digital twin into existing systems and processes can be complex and costly. Software development, updates to legacy systems, or adoption of new protocols and standards may be required.
- There may be regulatory requirements and compliance costs associated with digital twins to ensure that the system complies with industry standards and data protection regulations.

3.3.2. Before adopting a digital twin

In addition to going into the digital twin journey with their eyes open about possible costs, organisations should consider the questions below before developing or adopting a digital twin:

- Has the specific problem or challenge been thoroughly defined?
- Which use cases does the digital twin support?
- Is more than one digital twin project needed?
- How is data collected and made accessible? Will it be necessary to build or apply new physical infrastructure to collect data?
- What is the scope of a digital twin, in terms of, e.g., geographic coverage, number of assets, number of variables?
- What level of fidelity is required to achieve the goal?
- How can the digital twin be integrated into the existing system?
- How compatible are the systems?
- Is a tailor-made solution needed or can existing digital twin platforms be used?
- What cybersecurity measures are necessary?

- What regulatory requirements does the digital twin have to meet?
- Is there the necessary know-how in-house or will it need to be sourced externally?
- Has the full lifecycle cost of a digital twin been estimated – including elements like development, maintenance, updates and employee training?
- Will the benefits of a digital twin outweigh its costs (deployment/ maintenance/ consumption)?
- What is a long-term strategy for the digital twin?

Research by IoT Analytics indicated that despite the success of digital twins, 72% of organisations that embarked on a digital twin project reported facing a challenge with the cost of building digital twin solutions. As with any uncertain technology initiative, they suggest that adopters should:

- Assess their readiness to adopt digital twins in terms of the existing technology stack and the in-house talent. A number of 'legacy' software tools such as CAD, CAE and PLM – but also new tools such as IoT Platforms and the cloud – play an important role when developing digital twins.
- Quantify the benefits of the digital twin, and compare it with the opportunity cost of not implementing a digital twin for the respective use cases/proposed application.
- Design indicators that help measure progress. Certain digital twin projects take years before they materialise because ontology mapping, creating complex visualisations or developing suitable prediction algorithms sometimes take longer than anticipated (Hasan, 2023).

3.3.3. Proof of value

Kuguoglu et al. have put forward an interesting approach called 'proof of value' for pilot projects. They observed that technology-led implementations are often driven by 'cool' emerging technologies rather than solid business cases, and suggest that the value generated from new technologies should always be higher than the development and implementation costs, to maintain a healthy organisation. They propose to focus on business value over technology and to link the metrics of technology implementation success with overall equipment effectiveness, end-user statistics and reduction in maintenance costs or machinery downtimes. The end-goal is not only to prove that there is value but also to deliver it. This ultimately means that some pilots will fail because they either do not deliver meaningful value or are unable to scale. This approach works in favour of organisations, as it can save them from investing in projects that bring neither value nor scale – and not forgetting the learning and the knowledge transfer that can occur even if the project fails (Kuguoglu et al., 2021).

3.3.4. Defining KPIs

Key performance indicators (KPIs) are quantifiable metrics that help assess the performance of a project or undertaking against specific objectives or goals, and thereby build a critical step in measuring its success. Defining KPIs requires some strategic analysis, good communication between stakeholders engaged in the project, and data analysis. Given that they may fluctuate during the project, it is crucial to regularly review and update KPIs to ensure they are still relevant and applicable as the project evolves.

As presented in earlier sections, digital twins offer many advantages; however, these advantages must be quantified and validated. Without doing this, it is hard to build and evaluate a business case and calculate ROI. Appropriate KPIs will support better evaluation of digital twin systems, in order to manage them and improve their effectiveness. The literature provides general guidance and methodologies on how KPIs should be defined and their characteristics, but more targeted research into KPIs in the context of digital twin systems (e.g. how to measure implementation success and impact) is still limited at the moment (Psarommatis & May, 2023).

Exploring KPIs from outside the digital twin domain, a good example of a comprehensive and practical list is provided by Couraud et al. (2023). The researchers studied the UK's largest Smart Local Energy System (SLES) demonstrator in the Orkney Islands, named the Responsive FLEXibility (ReFLEX) project, and proposed a framework to help communities to successfully implement a SLES. They extended their Smart Grid Architecture Model (SGAM) into a comprehensive multi-vector Smart Local Energy Architecture Model (SLEAM), which includes all main energy services, namely power, heat and transport, and describes the main components and interaction layers that need to be addressed in a comprehensive SLES. Defining KPIs was a critical step to verify the success of the project, and the extensive list covers a number of categories, together with their description and how to compute them. These categories include energy, environment, society, economic, resilience, assets & infrastructure, data management, regulations and policies, extension and replication, and the full list (which is too long to include here) can be found in the paper at Annex A (Couraud et al., 2023). As transportation is closely linked to the energy sector, and shares some of the same challenges, the KPI list proposed by Couraud et al. can serve as a baseline for its further adaption into a transport digital twin environment.

One KPI-defining attempt worth noting is made by Psarommatis at al. They propose a novel structured method for measuring the performance and flexibility of digital twin methods such as simulations, analytics and visualisations. The flexibility of a digital twin method is defined as its ability to be used in different applications, and the ability to vary the initial methodology with as little intervention as possible. Furthermore, to increase the sustainability of digital twin development, they state it is necessary to reuse digital twin methods and models in different applications, rather than create a new model in each case. Because digital twin utilisation and technologies are fairly new to the industry, there is no standardised approach for evaluating the performance of digital twin implementations.

The study by Psarommatis at al. offers a common procedure for measuring the performance and flexibility of digital twins and an approach to directly compare digital twin implementations. The study proposes a structured methodology for calculating the performance of a digital twin model and for quantifying its flexibility, and they publish a questionnaire around the design of a digital twin methodology and information on the operational side of a digital twin. This helps to elicit relevant information from both the design and operational levels and increases the completeness, accuracy, measurement and flexibility of a digital twin methodology. The categories included in the questionnaire are:

- industry for which the digital twin is developed
- purpose of the digital twin
- process or asset described by the digital twin
- type of use of the digital twin (continuously, when needed, both, etc.)
- technologies used
- input parameters
- output parameters (Psarommatis & May, 2023).

This approach seems to be more of an academic nature, but it is a valuable step in developing metrics for industrial applications to measure the flexibility of digital twin methods in terms of their adaptability and scalability for various use cases.

3.4. Adaptability and scalability of digital twins

Following the proof of concept (or proof of value) and pilot stages of a new digital twin technology development is a large-scale roll-out. Scaling up means covering more assets, more people, more use cases and expanding the geographical coverage, while the simulated processes and goal remain the same. To give two examples of what large-scale digital twinning can mean in practice, Ford develops a digital twin for each model of vehicle it produces, while General Electric's digital wind farm is used to monitor more than 40,000 turbines across different sites.

Scalability is a crucial aspect of digital twin technology, as it determines the ability of digital twin systems to handle an increasing amount of data, assets, users and stakeholders, or complexity, as a business or organisation grows. As the number of data sources, including connected devices and sensors increases, so too does the amount of data generated. A scalable digital twin system should handle the addition of new assets without a significant increase in complexity or performance degradation. The performance of a digital twin system, including real-time monitoring, simulation and analysis, should remain responsive as the system scales, if it is a true representation of the physical asset. Therefore, organisations can only scale when they have a good understanding of what they have and what they need to scale. This may require efficient algorithms, distributed computing and hardware resources to handle the increased workload.

The adaptability of digital twin systems is just as important as scalability, particularly in dynamic environments such as smart cities. Digital twins need to reflect changing conditions and requirements, as well as accommodating new technologies, and digital twin systems should be flexible and easily adjustable enough to meet evolving needs. However, as more data is collected and shared through digital twins, security and privacy concerns become increasingly important, which brings the interoperability and data sharing to the forefront of any upscaling project. The lack of interoperability standards and methods, together with poor data sharing practices and culture create significant obstacles in large scale projects, e.g., smart cities or transportation.

It is important to note that as the volumes of highly diverse data increase, organisations should develop strong data management and operating models. The literature indicates that many systems seem to fall behind in this regard, and recommends that organisations invest in robust data practices for collecting, storing, structuring and maintaining such large volumes of data coming from a variety of sources, even before starting any digitisation initiatives. Data governance is not a one-off attempt but fundamental to successful digital transformation and the scalability, interoperability and flexibility of a data software tool like a digital twin. The literature calls for effective data policies for the continuous generation, usage, compression and decommission of data (Kuguoglu et al., 2021; Marcucci et al., 2020; Sharma et al., 2022).

To offset the costs of developing and running a digital twin, the market offers Software as a Service (SaaS) targeted at this emerging sector; this can decrease development and maintenance responsibilities and enable scaling-up.

3.4.1. Digital Twin as a Service

Digital Twin as a Service (DTaaS) is a cloud-based service that offers the capability to create and manage digital twins, and can represent a scalable and cost-effective approach to digital twin technology.

DTaaS is particularly valuable for companies that want to leverage digital twin technology without the burden of developing and maintaining the underlying infrastructure. Rather than being a general-purpose platform, it is designed for specific physical assets and includes common use cases and best practices typically required to monitor, manage and maintain those assets. For example, DTaaS for buildings is different to DTaaS for transportation and DTaaS for manufacturing. Due to the nature of the integration and the complexity of the product, DTaaS would almost always be sold in an enterprise model (Katzir, 2023).

From a business model perspective, DTaaS is simply Software as a Service (SaaS), a software licensing and delivery model that operates in the cloud. Unlike self-hosted products, there is no need to install, monitor or update the software on company-owned servers. In addition, DTaaS provides all the necessary security measures and patches, as these tasks are handled by the DTaaS provider (Katzir, 2023). In short, therefore, DTaaS can provide several advantages to organisations:

- DTaaS allows them to scale as needed, without significant investments in digital infrastrucutre.
- Organisations can avoid the upfront costs of building and maintaining on-premises digital twin infrastructure by using a subscription-based service. This can be especially beneficial for small and medium-sized businesses.
- It is easy for stakeholders to access and interact with digital twins from anywhere, using web browsers or mobile applications. This accessibility fosters collaboration and data sharing among teams and partners.
- DTaaS provides tools and services for integrating data from various sources, such as sensors, IoT devices and existing enterprise systems, into the digital twin environment.
- DTaaS can be integrated with other cloud-based services, such as data storage, machine learning and visualisation tools.
- DTaaS platforms include built-in analytics and AI capabilities to analyse data from digital twins and derive insights, predictions and recommendations.
- Robust security measures are already in place to protect sensitive data and maintain compliance with relevant regulations.
- Software updates, maintenance and infrastructure management are provided.
- DTaaS platforms offer options for customising digital twins to specific industry or application requirements, making it easier for organisations to tailor the service to their needs (Aheleroff et al., 2021; Katzir, 2023).

3.4.2. DTaaS platforms

DTaaS platforms are a critical component of the digital transformation process in various sectors, providing insights, efficiency, and innovation, but the choice of a platform depends on the specific industry, use case and requirements of each organisation. Examples of digital twin platforms include Siemens' MindSphere, Ansys, AnyLogic, Bentley System iTwin, Twin, PTC's ThingWorx, ArcGis Digital Twin Hub and Dassault Systèmes' 3DEXPERIENCE platform.

Below we present a selection of digital twin platforms in more detail:

- **General Electric (GE)** has been developing a digital twin environment integrated with different components of the power plant that takes into account customer-defined KPIs and business objectives by measuring asset health, wear and performance. Its digital twin runs on the **Predix™ platform**, designed to operate large volumes of sensor data at an industrial scale. The platform offers advanced distribution management solutions, geospatial network modelling solutions, grid analytics and asset performance management for power and utility services such as next-generation sensing technologies, digital threading, AI, advanced control and edge computing. Many world-renowned companies have applied the platform for diverse industrial fields including automotive, food and beverage, chemicals, digital energy, steel manufacturing, equipment manufacturing, pulp/paper manufacturing, and semiconductors (Rasheed et al., 2020).
- **ANSYS** introduced a digital twin builder in its ANSYS 19.1 version, providing developers with features such as creating a multi-domain system, multiple fidelity and multi-physics solver, efficient ROM construction capabilities, third-party tool integration, and embedded software integration, as well as system optimisation. ANSYS, along with other companies, built the digital twin for a pump that can use the real-time sensor data to improve its performance and to predict failures. General Electric also used a customised version of the ANSYS digital twin to design megawatt-sized electric circuit breakers (Rasheed et al., 2020).
- **Siemens' digital twin** leads the industry by offering diverse computational tools in CAE, CAD, manufacturing and electronic design and offers companies tremendous insight into products and designs. Siemens' plant simulation (PS) digital tool was successfully interfaced with a production line involving manufacturing of pneumatic cylinders within the automotive industry to promote

the concept of Industry 4.0. The production line simulation model was optimised by a genetic algorithm provided by Siemens' PS tool which adjusted the simulation model and then simulated the digital twin. Siemens' digital twin, powered by machine learning tools (e.g., recurrent neural networks), was demonstrated to complete the knowledge graph and synchronise the digital and the physical representations of a smart factory. Siemens made the Siemens Digital Enterprise Suite that can coordinate integrated software and automation solutions for industrial companies. The digitisation of communication networks helps MindSphere, one of Siemens' best IoT operating systems, get all the data it needs regularly (Rasheed et al., 2020).

- Azure Digital Twins is a software platform that offers the foundation on which to build the next generation of IoT solutions. It creates data-driven workspaces that combine all the necessary sources and develops new production technologies. Azure Digital Twins can be connected to Azure Stream Analytics, Azure AI, Azure Maps, Azure Storage, Microsoft Mixed Reality, Office 365, or Dynamics 365. IoT and AI platforms significantly reduce the complexity of creating digital copy solutions by enabling functions that trigger automatic endpoint actions based on incoming information. Azure Digital Twins utilises all environments, such as warehouses, offices, schools, hospitals, and banks, and can even be applied to factories, parking, stadiums, parks, intelligent grids and cities (Tomych, 2023).
- **Bosch** has built **Eclipse Ditto**, an open-source modular structure framework that builds a crucial bridge between real-world devices in the IoT space and their virtual twins, and helps devices communicate efficiently and directly over an API. The IoT devices can be connected via Eclipse Hono. It helps to interact with them uniformly regardless of the device communication protocol (HTTP, MQTT, and AMQP). Bosch pays extra attention to security and supports common authentication mechanisms like username/password and X.509 client certificates to verify a device's identity (Tomych, 2023).

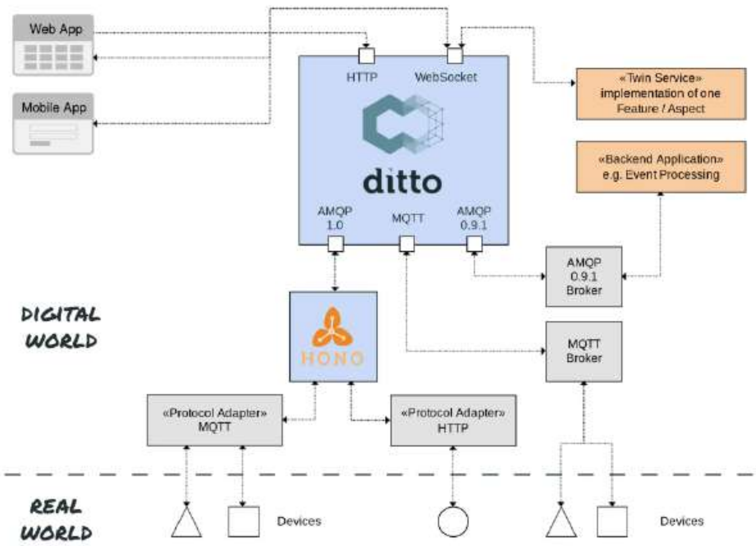

Figure 8 DT framework – Eclipse Ditto
Source : https://blog.bosch-digital.com/how-digital-twins-boost-development-in-the-iot/ (retrieved 15/10/2023)

- **SenSat** is a UK-based start-up concentrating on digital copies of real-world locations. Its solution, Mapp, is one of the most intuitive and easy-to-use cloud-based digital copies platforms, enabling its users to visualise and interact with multiple datasets. Visual representation allows for the control of physical projects digitally, in real-time, and provides the ability to discuss plans visually and intuitively. SenSat can put IoT sensors on a company's property and send the operational data and updates directly to the team in charge of spotting problems (Tomych, 2023).

3.5. Decarbonisation impact of digital twins

Computationally, running a digital twin environment using a conventional server architecture is a GHG contributor. In counterpoint to this, however, digital twins can have a significant positive impact on decarbonisation efforts, helping to reduce emissions and promote sustainability. By providing a comprehensive, data-driven view of systems, processes and assets, digital twins empower organisations to make informed decisions that contribute to decarbonisation efforts. They offer a powerful tool to optimise resource usage, reduce waste and lower GHG emissions across various sectors:

- ICT-based solutions could reduce commuting by 15-20% and cut GHG emissions by 10-15%, while local digital twins can significantly improve cities' ability to simulate or model the impact of policies. (Muench et al., 2022)
- Digital twins can model and simulate energy systems, such as buildings, industrial processes and power plants, to optimise energy consumption and reduce waste. By finetuning operations based on real-time data, organisations can lower energy usage and subsequently reduce their carbon footprint.
- EY found that digital twins can help to reduce the GHG emissions and the carbon footprint of existing buildings by up to 50%, alongside cost savings of up to 35%. (Bianzino & Yonge, 2022)
- By optimising the logistics and transportation of goods, organisations can reduce fuel consumption and emissions associated with the movement of products and materials.
- In the context of smart cities, digital twins can optimise traffic management, public transportation and urban planning. By reducing congestion and improving transportation efficiency, they can help lower emissions from vehicles and improve air quality.
- Digital twins can assist in the integration of renewable energy sources, such as solar and wind power, into the grid. They help manage and can predict fluctuations in energy production, making it more reliable and efficient, ultimately reducing reliance on fossil fuels.
- It is apparent that leveraging digital twins can significantly reduce energy consumption of the whole network. No matter how the number of tasks changes, the average delay and energy consumption of a digital twin-enabled scheme is always lower than that of the scheme without a digital twin. (Wang & Lin, 2022)
- Digital twins can track the carbon footprint of products, services and operations by monitoring and analysing data throughout their life cycle. This helps organisations to identify areas where emissions can be reduced and make more environmentally-responsible decisions.
- Simulating the operating performance of heating, ventilation and air conditioning systems in a virtual environment can help to de-risk novel applications by facilitating an understanding of their functionality in achieving a healthy and pollution-free environment, as well as in reducing energy consumption by building occupants. (Tzachor et al., 2022)
- Digital twins provide cities with better knowledge of the currently unused potential and opportunities of their areas. They also provide a comprehensive inventory of green and blue infrastructure as well as a diagnosis of land use. By simulating different greening scenarios, digital twins help identify priority areas for greening and the best action plans for smarter urban planning and more nature-friendly cities. (Gabory, 2023)
- Fraîcheur de Paris, the operator of the urban cooling network of the City of Paris, utilised digital twins to monitor the impact of new district heating and cooling networks on environmental indicators such as air quality, noise or pollutant emissions. Digital twins likewise enable planners of district heating and cooling networks to better predict energy demand. Gains include the reduction of unnecessary site visits and improved network planning. (Gabory, 2023)

A closer look at Helsinki:

In the previous chapter, we mentioned Helsinki in the context of bike-sharing, but the city's achievements in the context of digital twins reaches much further. The Finnish capital is a world leader in using digital models as tools to achieve its ambitious and rapid decarbonisation goal by 2030, and it is looking to harness the potential of geothermal energy with the help of local homeowners. The Helsinki digital twin is in fact two models: a reality model and a semantic City GML (short for Geography Markup Language, an international standard in mapping software). The reality model comprises pictures and is made up of two billion polygons, while the semantic model is the underlying brains, with data layers that can be labelled, interrogated, added to and changed. The team has analysed the hours of solar radiation across the year, and also the shadows cast by built or to-be-built structures as they fall on parks, pavements and other buildings, since both variables impact the efficacy of solar panels for energy production. The open-source platform allows any landlord or resident to consult the model and look up on their mobile phone the solar potential of any given roof space. The city has conducted solar radiation and shadow analysis on 1 million surfaces in the built and to-be–built environment, to allow developers and existing owners to calculate the actual benefits of solar panel installation, and the most efficient placements for panels. The data within the digital twin is vital to be able to demonstrate the benefit of tapping into these energy resources and to ultimately replace the current mix of coal-fired, nuclear and hydroelectric sources for district heating. Equally, each building has an energy rating that enables the calculation of the effects of renovation or improved insulation against current fossil fuel-based energy consumption (Murray, 2022).

3.6. Making digital twins green

The green transition is relevant to digital technologies because they too have to reduce their impact on global climate change. The expansion of digital infrastructure must be kept in line with the aims of the green transition, particularly regarding the energy consumption and the environmental footprint of such digital infrastructure (Muench et al., 2022).

When it comes to digital twins, multiple layers of the architecture must become climate-friendly. Physical infrastructure, such as sensors, IoT devices and gateways, must become (even) more energy -efficient and sustainable in terms of materials and processes applied in the production. Keywords here are bio-based electronics and energy-harvesting devices. With regard to the digital infrastructure, its physical representation is the data centres (hyperscale data centres, or the 'cloud') that run on massive servers that store and process the data. As reported by Ernst & Young, hyperscale infrastructure represented 45% of data centre energy demand in 2021, up from 16% in 2015 (Bianzino & Yonge, 2022). Here, quantum computing or neuromorphic hardware can offer a more efficient and environmentally-friendly approach (Muench et al., 2022).

By considering sustainability at every stage of the digital twin lifecycle, from design and implementation to operation and disposal, organisations can reduce the environmental impact of digital twin technology while harnessing its benefits for optimisation and efficiency. Ideas from the literature on how to make a digital twin green include:

- Optimise the underlying digital twin infrastructure for energy efficiency, using green data centres, efficient servers and cooling systems.
- Implement energy-efficient hardware and technologies for data collection, processing and communication, such as low-power sensors and IoT devices.
- Employ data compression and data reduction techniques to minimise the amount of data transmitted and stored, reducing energy and storage requirements.
- Use data lifecycle management to automatically delete or archive data that is no longer relevant, reducing the storage footprint.
- Plan for the disposal or recycling of digital twin hardware and infrastructure components in an environmentally-responsible manner.
- Conduct a lifecycle assessment of the digital twin infrastructure to identify areas where energy and resource efficiency can be improved.

- Implement monitoring tools to track the energy consumption and carbon footprint of digital twin operations and regularly report on sustainability efforts.

To reiterate a point from Chapter 2 (2.4.2.), it is important to approach digital twin deployment consciously and to look beyond the standard narrative of the benefits from digital twin systems. With large scale-digital twins in particular, it is advisable to carefully examine the cost-benefit ratio that goes beyond the classic economic calculation. The latest report of the AIOTI on "IoT and Edge Computing Carbon Footprint Measurement Methodology" (September 2023) provides the necessary guidance on methodologies for measuring ICT carbon footprint. It includes a method of calculating the avoided carbon emissions in an industrial sector/domain when ICT is used as an enabling technology.

More information on green digital twins can be found in Chapter 5 (5.8. and 5.9).

3.7. Conclusion

Due to their enormous potential benefits, digital twins have gained widespread attention and adoption across industries ranging from manufacturing to healthcare to smart cities, and as technology and best practices advance, more quantifiable evidence could be provided to confirm many of the claims in their favour. Digital twins are seen as a key enabler of Industry 4.0 and its highly automated manufacturing processes that require high-speed connectivity, advanced IoT systems and analytics. Digital twins can bundle these technologies into a useful operational model to optimise diverse processes, uncover hidden patterns in complex data streams and create more transparency through data.

However, a digital twin is still a somewhat problematic concept, as it is debatable whether it should be considered an emerging technology or a mature one. On the one hand, industries such as aerospace and manufacturing have been using digital twins for a few decades, and Global Market Insight has said that the size of the digital twin market, estimated in 2022 at $8 billion, is expected to grow at around 25% Compound Annual Growth Rate (CAGR) from 2023 to 2032. On the other hand, in 2018, Gartner estimated that digital twins are 10 years away from the 'plateau of productivity' (which meant 10 years from mainstream adoption). While in 2023, we see substantial digital twin adoption activity, ranging from early-stage pilots to complex system implementations. Digital twin technology has spread to numerous industries with varying levels of digitalisation, giving rise to a wide range of maturity – from having some highly advanced digital twins in some sectors to 'early adopter' digital twins in others. On the question of whether digital twins are an emerging technology, the fact the digital twins pull together various existing technologies that have reached high technical maturity means they cannot be considered an emerging technology in that respect. However, what is 'emerging' about digital twinning are the use cases and applications of digital twins and the sectors into which they have penetrated.

This leads us to another observation that the use of digital twins is an obvious way of doing things in the digital twin-experienced sectors, whereas sectors just starting their digital twin journey need more support to understand exactly how digital twinning can be used, what problems it addresses and how to measure implementation success. As shown in the earlier section on implementation costs, going for digital twin development is a critical strategic decision in an organisation since it demands significant investment on multiple levels including ICT/data infrastructure set-up and maintenance and staff training. Therefore, it is important to develop a strong business case, and to understand the ROI. However, the thinking around digital twin implementation should go way beyond the business case process because digital twinning is not just a tool that is used for certain tasks; rather, it changes the way an organisation operates, how it purchases assets, how it maintains and decommissions them, and how it internally manages its own processes (procurement, staff training, internal policies, data governance). Consequently, change management is an important topic for any organisation when it decides on digital twin adoption.

To sum up, this chapter has highlighted several matters relevant in advancing digital twins for transport, all requiring further research:

- Capturing human behaviour in data models, e.g., in urban mobility digital twins.
- Understanding how human behaviour affects the accuracy of digital twin analysis and how fast a digital twin can adapt to new socio-economic occurrences.
- Defining KPIs to measure the success of digital twin implementation in transportation – this is related to the problem articulation that should be addressed with any digital twin.
- Defining a KPI framework to measure flexibility, scalability and accuracy of digital twin methods – e.g., how easily can a digital twin method adapt to a new use case, and how much modification does it require?
- Guidance on problem definition and business case development for digital twin implementation. Defining a practical set of questions could be considered, e.g., what new insights into the operations/assets are needed, and how to integrate asset X with asset Y.

Digital twinning is a highly technology-driven trend; yet, to become part of the mainstream, a socio-economic and environmental narrative is needed in order for it to find a stronger anchor in strategic business operations and face fewer obstacles to its real-world implementation.

4. WP3 Physical infrastructure components for transport digital twins

This chapter introduces and explores the cyber-physical infrastructure for the transportation digital twin, discussing the role and relevance of sensor systems and communication infrastructure. Briefing is provided on the sensing modalities, relevant sensors or systems and their impact, in relation to four transportation modes: road, railways, marine, and aviation.

The Ihapter then moves on to look at sensors and systems connectivity and data interoperability, and then to discuss digital twin architecture. The penultimate section highlights sensor data security reliability and quality issues, and the chapter finishes by noting knowledge gaps in this area.

4.1. Use of sensors in the digital twin

A sensor device is a physical tool designed to measure and observe one or more physical phenomena such as temperature, gas or speed. An observation represents a measurement of a specific event at a particular place and time, derived from a singular stream of data generated by a sensor. This stream of data, known as a sensor stream, comprises a continuous sequence of observations produced by a sensor device. Multiple sensor devices with common features, like those from a particular manufacturer, can collectively form an integrated sensor system and operate under similar access protocols. The above definitions serve as the foundation for cataloguing, accessing and organising data. A number of sensors along a node using electronic communication to transfer data to a repository for further processing is then an IoT system.

The swift progress of the IoT, coupled with cost-effective communication technology and the shrinking size and power demands of sensors, has triggered a notable increase in environmental and infrastructure sensing within urban environments. IoT sensors have emerged as essential tools, offering real-time data, constant monitoring and substantial data streams across a range of urban parameters. These sensors have played a central role in the evolution of smart cities and are pivotal in tackling urban issues such as air quality improvement, climate change adaptation, and the shift towards a low-carbon economy. They also represent crucial elements in the establishment of digital twins for transportation systems. There are three main components of a digital twin: hardware, data management middleware, and software. These components form the structure of the digital twin ecosystem as reflected in Figure 9. This section will essentially describe the hardware component and will cover use of sensors and their applications relevant to transport digital twin.

Figure 9. Digital twin components (Patnaik, 2023)

4.1.1. Use of sensors for digital transportation

Numerous potential use cases arise from the integration of advanced sensor technology and data analytics. These applications encompass diverse areas, including the reduction of carbon emissions in transportation, particularly in the context of electric freight connections and the management of multimodal transportation networks. Additionally, the technology facilitates the mapping of optimal locations for active travel hubs and introduces passive methods for discerning journey modes and purposes, thereby providing more accurate data than was previously available in periodic census information and enabling the capability for optimisation.

Moreover, the deployment of sensors could, for example, allow for the collection of emissions data at bus shelters and transport hubs, assisting in environmental monitoring and decision-making regarding transportation hub locations. These sensors can also provide information about the clustering of individuals, providing valuable insights for hub placement decisions and contextualising the cost of various transport modes. Furthermore, the technology offers an opportunity to assess the impact of congestion charges on behaviour, capturing both intended and unintended consequences across traffic, public transport, and active travel modes.

In the realm of transportation network management, the use of sensors supports predictive incident analytics and real-time notifications for targeted interventions, fostering a more efficient and responsive system. This technology also facilitates the comparison of conventional sensor data with information obtained from non-traditional sources, enhancing the depth and breadth of insights. Lastly, it allows for the collection of out-of-vehicle trip and travel data, providing a comprehensive view of transportation patterns and behaviour.

4.1.2. Use of sensors for transport decarbonisation

Looking more specifically at the use of sensors in the decarbonisation of transportation of systems, a growing number of options has been identified, ranging from eVs to commercial shipping. A selection is provided below.

Sensors on eVs and EV charging points: In addition to the carbon emissions reduction achieved by eVs' consumption of green electricity rather than fossil fuels, the use of embedded sensors within eVs can play a critical role in monitoring fuel consumption and optimising routing. These sensors can be connected to smartphones, empowering vehicle owners to efficiently manage and potentially sell surplus power back to the grid through a vehicle-to-grid (V2G) system (Virta, 2023). Furthermore, charging point sensors serve as location beacons for approaching eVs, eliminating the unnecessary emissions generated when searching for charging stations. These sensors can also contribute to the grid by facilitating the redistribution of excess power, making it available for other purposes.

IoT telematics: Telematics integration within engine and navigation systems serves to enhance speed, fuel efficiency and overall vehicle performance. Embedded telematics comprise approximately half of the projected connected car IoT connections, according to Global System for Mobile Communications Association (GSMA) Intelligence forecasts. This technology is also witnessing increasing adoption across sectors such as heavy-duty vehicles (HGVs), commercial ships and rail transportation. The reduction in CO2 emissions primarily results from reduced travel distances and the refinement of acceleration and deceleration patterns, but there is an additional benefit through curtailing idling periods, which subsequently reduces fuel wastage. This progress supports the transition to a just-in-time delivery model (a management strategy that aligns raw-material orders from suppliers directly with production schedules), a paradigm applicable to both maritime and trucking operations at ports, as well as rail transportation. Routing optimisation using smart sensors and IoT can help reduce carbon emissions (Tim Hatt, 2022), with some specific examples presented here.

Heavy goods vehicles (HGVs): A Statista study on the 'distribution of carbon dioxide emissions produced by the transportation sector worldwide in 2022, by sub sector' s 16% emission is contributed by heavy freight vehicles in the transportation sector (Virta, 2023). Here, emissions can be reduced by the application of connected telemetry sensors on board, which are instrumental in route optimisation and speed management for HGVs. This translates into CO2 reduction by minimising the distance travelled and optimising the coordination of consignment pick-ups and deliveries. A CENSIS-supported project by Icon Research found that sensing the 'top dead centre' position of the engine crankshaft allows for greater fuel efficiency (Censis, 2017).

Commercial shipping**:** In commercial shipping, sensors and telemetry can account for 21% of the total emissions reduction within the transportation sector (European Automobile Manufacturers Association, 2020). This can be achieved by utilising onboard connected telemetry sensors to enhance route selection and vessel speed, improved scheduling, and collaboration with port authorities to synchronise arrival times with subsequent HGV shipments, thus diminishing unnecessary idle periods.

A real-life example of this is the company **Maersk** which created an IoT-enabled container ship equipped with logistics management features (Shakib, 2019). This was achieved through the installation of sensors on containers and various onboard equipment. This software enables the organisation to oversee fleet performance comprehensively, encompassing aspects such as fuel efficiency, while also offering the ability to finetune routing and coordinate port arrival times to coincide with available slots and subsequent truck deliveries (*Technology at Maersk*, n.d.).

4.2. Further examples and use case scenarios in various transport modes

This next section provides selected examples of sensors being used in operation in key transportation types, starting with smart road use cases, and then moving onto train/metro networks and maritime scenarios.

Smart road use cases

A contract was awarded (2021) to Vivacity Labs to install 100 sensors, by Transport for Greater Manchester (TfGM), across the region to monitor cycling and walking schemes (Kono, 2021). The datasets will enable TfGM to understand how active travel users are interacting with schemes and to evaluate their effectiveness in facilitating walking and cycling.

To achieve a carbon footprint reduction in fleets (municipal vehicles, buses, trucks), municipalities are installing affordable IoT sensors to capture emission levels, temperature changes and other real-time environmental data, and then leveraging these insights for modelling new transport management scenarios. The next step is the development of intelligent infrastructure solutions such as smart traffic lights, connected CCTV cameras for accident/road traffic monitoring, smart parking systems, and more ubiquitous connectivity between road users, physical infrastructure and digital transport management systems.

The data that comes from vehicle and roadside sensors, such as cameras, and smart analytics can predict if a traffic jam is likely to occur and provide a richer picture of what is ahead. This helps drivers to optimise their speed and reduces the chance of a build-up of vehicles on the road, thus reducing the emissions associated with traffic jams.

Train/metro network use cases

Equipped with high-performance connected sensors, a train or metro train will be able to detect any obstacles not only on its own track but also on parallel tracks, to automatically alert track teams, plan on-site work or even resolve the issue remotely, helping to save energy. Station supervision systems will have the ability to analyse energy consumption in real time, so determining exact energy needs depending on passenger flows, e.g., to ensure that energy consumption matches requirements as closely as possible while guaranteeing expected levels of performance and without sacrificing passenger comfort. We can legitimately assume that a greater density of passenger flow will reduce the number of car trips, which consume more energy (in carbon generated per person and per km travelled) than train trips.

The multinational Thales develops complex AI systems that promote eco-responsible AI based on learning and knowledge and consume less energy (*How Can Artificial Intelligence Help Build a Greener Future?*, 2023). Driver assistance systems (GreenSpeedTM), traffic management systems (TMS) and systems to manage the automatic operation of metros (GreenCBTC) and autonomous trains (RailBotTM) optimise energy consumption through carefully defined driving strategies and by calculating optimal acceleration and braking profiles in real time. Anticipating incidents on the network is also an important factor in reducing unplanned train stops caused by obstacles on the tracks. Equipped with high-performance connected sensors, a train will be able to detect any obstacles on its own or parallel tracks, helping to save energy. Station monitoring systems will analyse energy consumption in real time, and the train's sensors will determine exact energy needs based on passenger flows.

A company known as VS1 Sensors offers innovative sensor system products designed to alleviate traffic congestion by optimising use of existing infrastructure. In-road sensors can detect any vehicle and traffic patterns without using cameras (*Disruptive Engineering Next-Generation Road Sensors for Sustainable Transport*, n.d.).

A minibus called Olli, produced by Local Motors, already moves around the EUREF-Campus site without a human driver, controlled by sensors and generating no emissions. Although this vehicle is still being tested in operation, transportation solutions like Olli are set to become a central element of multimodal transport (Grace, 2016).

Maritime scenario use cases

The digitisation of maritime routes, ports and the broader supply chain is driving innovation in both technology and business models. This transformation encompasses a holistic approach to maritime transport, integrating sensor technologies, advanced networking, smart information processing and control systems. High-speed broadband communication, facilitating seamless connectivity between ships and between ships and shore, forms the backbone for traffic optimisation and control mechanisms. Simultaneously, these networks provide the foundation for highly automated support systems, including the advent of autonomous shipping. These advances are not only revolutionising the way maritime traffic and ports are managed but are also extending their reach into inland logistics, creating a comprehensive digital ecosystem.

4.3. Sensors and systems

4.3.1. Roles, relevance, examples, and potential for various modes of transport

Sensors are essential for enabling data-driven transport management, planning, forecasting and decision-making, coming in various forms and an array of measuring factors such as telematic data, air quality, traffic patterns, weather conditions, infrastructure health and noise levels. The range of potential sensing devices is enormous, but most of the sensing in relation to digital transport twins focuses on transportation or mobility-related metrics. The role of the sensor and its application in digital transport twins is reflected below.

- **Collection of real-time data about transportation systems**: this data includes vehicle counts, speed, environmental conditions, and more. Examples include traffic cameras, GPS trackers, air quality sensors and vehicle health sensors. The potential of data collection sensors lies in enabling data-driven decision-making, optimising operations, and enhancing safety and efficiency.
- **Monitoring and control:** sensors provide continuous monitoring of various aspects of transportation infrastructure and vehicles. Examples include traffic light sensors, structural health sensors, vehicle tracking systems and pedestrian detectors. Monitoring and control sensors enable real-time monitoring and control of traffic flow, infrastructure health and safety.
- **Safety enhancement**: sensors play a crucial role in detecting accidents, hazards and unsafe conditions on the road or in public transportation systems. Examples include collision detection sensors, pedestrian detection sensors, road condition sensors and airbag deployment sensors. Safety enhancement sensors like these have potential to improve road safety, reduce accidents and enhance emergency response.
- **Environmental impact assessment**: sensors can measure environmental parameters such as air quality, helping to assess and mitigate the environmental impact of transportation. Examples include air quality sensors, sound sensors, emission sensors and weather stations, and they can support sustainable transportation planning, reduce pollution and improve air quality.
- **Efficiency optimisation:** sensors can help optimise transportation systems and efficiency, reduce congestion or energy consumption, and improve traffic management. Examples include traffic flow sensors, parking space availability sensors, energy usage sensors and route optimisation sensors.

3.4.2 Sensing modalities and sensors for transport information

Sensing modalities for transport information encompass a diverse array of technologies and methodologies designed to collect and analyse data pertaining to transportation systems. These modalities include specialised instruments such as air quality sensors, instrumental in monitoring environmental health factors such as carbon monoxide levels and humidity. Traffic sensors, notably through the use of automated number plate recognition (ANPR) and closed-circuit television (CCTV) technology, are integral to the precise measurement of journey durations and vehicle counts. Pedestrian counts, facilitated by CCTV sensors, provide valuable insights for urban planning and infrastructure management. Weather sensors record meteorological data such as air temperature, precipitation and wind, vital for both city planning and safety considerations. Furthermore, infrastructure sensors contribute to road maintenance by monitoring road surface temperatures, ensuring the integrity of road networks – e.g., road temperature sensors have been used to optimise council gritting operations. Finally, noise sensors, by monitoring ambient noise levels, offer crucial support in urban noise pollution control. Each of these sensing modalities plays a unique role in the comprehensive gathering of transport-related data, collectively advancing the development of digital models for transportation systems. A range of sensing modalities are critical for gathering transport-related data, with each modality serving a unique role in gathering transport information, collectively contributing to the creation of transport digital twins. Below, we summarise the sensing modality, sensors and their impact for various transport application scenarios: road transport (He et al., 2019) presented in Table 6, rail transport (Baasch et al., 2018, Tagiew et al., 2023, and "The Internet of Trains," n.d.), presented in Table 7, marine transport presented in Table 8 and aviation presented in Table 9.

Table 6. Sensors in road transport applications

Transport application	Purpose	Sensing modality	Major sensor examples	Potential impact or contribution	Potential knowledge gaps regarding decarbonisation
Traffic management	Optimise traffic flow and reduce congestion	Count vehicles on roads	Inductive loop sensors, infrared sensors	Improved traffic flow and congestion management	Scalability and reliability of real-time data collection.
		Measure vehicle speed	Doppler radar, LiDAR	Identify areas with traffic issues	
		Detect red light/stop sign violations	CCTV cameras, licence plate recognition	Enhanced traffic safety	
Parking management	Efficient parking space utilisation	Detect available parking spaces	Ultrasonic sensors, magnetic sensors	Reduced time spent searching for parking	Integration with smart parking systems and privacy concerns
	Streamline payment and ticketing	Automate payment processing	Contactless payment systems, QR code scanners	Convenient and efficient parking facilities	
Public transportation	Optimise routes and schedules	Monitor passenger numbers	Infrared passenger counters, ultrasonic sensors	Improved public transportation services	Integration of real-time data into transit operations
	Provide real-time updates	Offer arrival/departure information	GPS, RFID	Enhanced passenger experience	
Environmental monitoring	Assess environmental impact	Measure air pollution levels	Gas sensors, particulate matter sensors	Evaluate and manage pollution levels	Sensor calibration and placement for accurate data
	Monitor noise levels	Measure noise pollution levels	Microphone-based Noise Sensors	Mitigate noise pollution	
Road safety	Enhance road safety	Detect accidents or collisions	Radar, LiDAR	Prompt emergency response and safety improvement	Sensor reliability in adverse weather conditions
	Optimise road maintenance	Assess road conditions	Road surface temperature sensors, moisture sensors	Safer and well-maintained road infrastructure	
Fleet management	Track vehicle location and status	Monitor vehicle location and status	GPS receivers, telematics units	Efficient fleet operations and maintenance	Data integration and privacy concerns
	Monitor vehicle health	Check vehicle condition and maintenance needs	OBD-II sensors, tyre pressure sensors	Improved vehicle performance and longevity	
Pedestrian safety	Improve pedestrian safety	Identify pedestrians at crosswalks	Infrared sensors, LiDAR	Safer interactions between pedestrians and vehicles	Accurate detection and privacy considerations
	Maintain pavement infrastructure	Assess pavement conditions	Pressure sensors, vibration sensors	Safer and well-maintained sidewalks	
Energy efficiency	Monitor and optimise energy usage	Track energy consumption	Fuel flow sensor, oxygen, wheel speed sensor, tyre pressure, transmission, load sensors	Energy savings and sustainability	Accuracy and data integration into vehicle systems
Supply chain management	Optimise supply chain logistics	Monitor location and condition of goods	RFID tags, GPS trackers	Efficient supply chain operations	Data integration, cargo tracking, and security
Smart infrastructure maintenance	Ensure infrastructure integrity	Structural health sensors	Monitor bridges, tunnels, etc.	Prevent infrastructure	

				failures and accidents	
	Control signage and lighting	Sensors for signage and lighting	Adjust road signs and lighting	Improved road safety and energy efficiency	
Emergency response	Rapid incident detection and response	Incident detection sensors	Detect accidents, fires, etc.	Faster emergency response times	
Data analytics and predictive modelling	Predict future trends and needs	Various sensors (e.g., traffic, weather)	Collect data for modelling and analysis	Informed decision-making and planning	
Security and surveillance	Enhance security and surveillance	Video and audio sensors	Monitor transportation hubs and infrastructure	Improved security and safety	
Passenger experience	Enhance passenger satisfaction	Passenger feedback sensors	Collect passenger feedback	Improved services and passenger satisfaction	

Table 7. Sensors in rail transport

Transport application	Purpose	Sensing modality	Sensor types	Potential impact or contribution	Potential knowledge gaps regarding decarbonisation
Energy efficiency	Monitor energy usage and optimise systems	Electrical	Current sensors, voltage sensors	Reduce energy consumption and emissions	Integration with railway infrastructure and data privacy
Track condition	Monitor track condition for maintenance	Mechanical	Accelerometers, strain gauges	Prevent derailments, reduce maintenance costs	Sensor reliability in harsh weather and remote areas
Passenger safety	Ensure passenger safety	Visual, infrared	CCTV cameras, thermal imaging	Enhance safety and security	Privacy concerns, data storage and image analysis
Autonomous trains	Enable autonomous train operation	LiDAR, radar	LiDAR, radar, GPS	Improve efficiency and reduce emissions through autonomous control	Sensor reliability and safety in autonomous systems
Train positioning	Precisely locate and control train position	GPS, GNSS	GPS receivers, GNSS antennae	Optimise routing and reduce fuel consumption	Accuracy and signal loss in tunnels or urban areas
Air quality monitoring	Monitor air quality in stations and trains	Chemical, environmental	Gas sensors, particulate sensors	Improve passenger health and reduce emissions	Sensor calibration, placement, and data integration
Passenger counting	Track passenger numbers for service optimisation	Infrared, ultrasonic	Infrared sensors, ultrasonic sensors	Optimise service frequency and reduce energy usage	Accuracy and privacy concerns in passenger counting.
Maintenance predictive	Predict maintenance needs for rolling stock	IoT, telemetry	Vibration sensors, temperature sensors	Reduce downtime and maintenance costs through predictive maintenance	Data analysis and integration with maintenance systems
Noise monitoring	Monitor noise levels for environmental impact	Acoustic	Microphone-based noise sensors	Minimise noise pollution and environmental impact	Sensor accuracy and data analysis for noise levels

Table 8. Sensors in marine transport applications

Transport application	Purpose	Sensing modality	Sensor types	Impact or contribution	Potential knowledge gaps in sensors regarding decarbonisation
Cargo monitoring	Track cargo identity,	Electronic ID, location,	RFID, GPS, temperature sensors	Optimise cargo handling, reduce	Data integration and security of cargo tracking

	conditions and status	environmental data		spoilage and emissions	
Fuel efficiency monitoring	Monitor fuel consumption and engine performance	Fuel and engine parameters	Fuel flow sensors, engine control units	Reduce fuel consumption and emissions	Real-time data accuracy and sensor reliability
Emission monitoring	Measure greenhouse gas emissions	Chemical, environmental	Emission sensors, gas analysers	Comply with emissions regulations, reduce carbon footprint	Sensor calibration and accuracy for compliance
Route optimisation	Optimise vessel routes for fuel efficiency	GPS, environmental	GPS, weather sensors, AIS	Reduce voyage times and fuel consumption	Integration of weather and vessel data for optimisation
Hull condition monitoring	Monitor the condition of the vessel's hull	Ultrasonic, mechanical	Ultrasonic sensors, vibration sensors	Prevent biofouling and hull degradation	Sensor placement and maintenance in harsh marine environments
Passenger safety	Ensure passenger safety and security	Visual, infrared	CCTV cameras, thermal imaging	Enhance passenger safety and peace of mind	Privacy concerns and image data storage
Autonomous navigation	Enable autonomous navigation and collision avoidance	LiDAR, radar, acoustic	LiDAR, radar, sonar	Improve vessel navigation and safety	Sensor reliability in maritime conditions
Port operations	Optimise port logistics and cargo handling	RFID, environmental	RFID, IoT sensors, crane sensors	Streamline cargo operations and reduce waiting times	Data integration and security in port logistics

Table 9. Sensors in aviation applications

Transport application	**Purpose**	**Sensing modality**	**Major sensor examples**	**Potential impact or contribution**	**Potential knowledge gaps regarding decarbonisation**
Aircraft health monitoring	Monitor the condition and performance of aircraft systems and components	Collect data on various aircraft parameters, such as engine health, airframe stress, and temperature	Inertial measurement units (IMUs), engine sensors, pressure sensors, temperature sensors, vibration sensors	Enhance aircraft safety, reduce maintenance costs, and improve operational efficiency	Sensor redundancy and fault tolerance
Flight data recording	Record flight parameters and events for analysis and investigation	Continuously record flight data and cockpit voice to aid in accident investigation and performance analysis	Flight data recorders (black boxes), sensors for speed, altitude, attitude and GPS	Improve aviation safety, support accident investigations, and enhance aircraft design	Data storage and retrieval challenges Real-time integration to digital twin on ground
Aircraft navigation	Assist in precise aircraft positioning and guidance during all phases of flight	Provide accurate position, velocity, and altitude information for navigation and landing	GPS receivers, inertial navigation Systems (INS), radar altimeters	Enhance navigation precision, reduce the risk of collisions, and improve airport operations	Signal interference and GPS reliability
Weather monitoring	Monitor weather conditions and hazards affecting flight safety	Detect and track weather phenomena, such as storms, turbulence, icing, and lightning	Weather radar, lightning detectors, temperature and humidity sensors	Improve flight safety by providing real-time weather information to pilots and air traffic controllers	Limited coverage and accuracy of weather data Real-time integration to digital twin on ground and in air
Aircraft fuel efficiency	Optimise fuel consumption and reduce emissions	Monitor fuel flow, engine efficiency, and air data	Fuel flow sensors, air data sensors,	Reduce fuel costs, lower emissions, and enhance	Integration challenges and data accuracy

		parameters to optimise flight profiles	engine efficiency sensors	sustainability in aviation	
Aircraft structural health	Monitor the structural integrity of aircraft components and airframe	Measure structural loads, stress, and damage to assess the health of aircraft components	Strain gauges, load cells, acoustic emission sensors	Improve aircraft safety by detecting structural issues and ensuring timely maintenance	Sensor placement and calibration complexities
Cabin environment monitoring	Ensure passenger comfort and safety by monitoring cabin conditions	Monitor cabin air quality, temperature, and humidity to enhance passenger comfort	Cabin air quality sensors, temperature sensors, humidity sensors	Improve passenger experience, health, and well-being during flights	Sensor maintenance and calibration
Aircraft security	Enhance security measures and detect unauthorised access or threats	Monitor cabin and cockpit security, detect intrusions, and record security-related events	Surveillance cameras, door and hatch Sensors, intrusion detection sensors	Enhance aviation security and deter potential threats or unauthorised access	Privacy concerns and false alarms

4.4. Sensors and systems connectivity and data communication

Communication technologies are pivotal in enabling digital twins within the transportation sector. These digital replicas heavily depend on real-time data exchange and remote monitoring, which are vital for creating virtual representations of physical assets and systems. Digital twin technology seems to have gained significant traction in the transportation industry, aiming to enhance the efficiency, safety and sustainability of various transportation modes, from cars and trains to ships and aircraft. However, to harness the full potential of digital twins in transportation, a robust communication technology infrastructure is essential. Given the dynamic nature of digital twin technology, this infrastructure must be adaptable and agile to accommodate emerging advancements and evolving industry needs. Moreover, fostering collaboration and standardisation across the transportation sector is crucial to ensure seamless integration and interoperability of digital twins across diverse modes of transportation and geographic boundaries.

4.4.1. Communication technologies and implication

Many of the potential sensor devices for transport digital twins currently rely on 3G, 4G or 5G technologies to transmit data packets. These protocols are well-suited for devices requiring relatively high bandwidth, particularly those handling video streams, and they accommodate higher density data transmission. More recently, IoT sensors have started to leverage specialised communication protocols, such as LoRaWAN and Narrowband IoT (NBIoT), which offer cost-effective and simpler set-ups but are less suitable for high-bandwidth applications. Wi-Fi has become a less common choice for data transmission in this context. Sensor devices may transmit data continuously, as observed with CCTV video feeds, but typically, they report data at regular intervals, with observation cycles spanning from 1 to 15 minutes. This diverse range of communication technologies allows for the flexibility needed to meet the specific demands of digital twin technology in the transportation sector.

A summary of typical digital communication technologies and their potential for transport digital twin is provided in Table 10.

Table 10. Various communication technologies and their potential for transport digital twins

Communication technology	Description	Implications for digital twin	Specific relevance for road transport	Specific relevance for rail transport	Specific relevance for marine transport	Specific relevance for air transport
Wi-Fi	Enables remote monitoring	Real-time data collection	Real-time monitoring	-	-	-
Bluetooth	Short-range, low power	Limited data transfer	Vehicle-to-vehicle communication	Train car-to-car communication	-	-
Cellular 2G, 3G, 4G, 5G	Wide coverage, high speed	Data costs and security	Fleet tracking and management	Train infrastructure monitoring	Fleet tracking and logistics	In-flight data connectivity
Ethernet	Stable, high-speed wired	Limited mobility	Infrastructure connectivity	Onboard train systems connectivity	Onboard ship systems connectivity	Onboard aircraft systems connectivity
Zigbee	Low-power, short-range	Suitable for sensors	Sensor networks for road conditions	Train sensor networks	Ship sensor networks	Aircraft sensor networks
NFC	Close-range communication	Limited data capacity	Contactless ticketing and payments	Contactless ticketing for rail	Contactless ticketing for ferries	Contactless boarding and payments
Satellite	Long-range, global coverage	High latency, expensive	Remote areas and global tracking	Remote rail routes and tracking	Maritime tracking in open waters	Global tracking and communications
Optical / Laser	High-speed data transmission	Line-of-sight, limited mobility	High-speed data transfer	Line-of-sight rail signalling	Optical data communication	Line-of-sight communication
Acoustic	Uses sound waves for data	Limited data capacity	-	-	Underwater sonar for navigation and communication	-
Wired	Physical cable connection	Stable, high-speed	Infrastructure connectivity	Railway signalling systems	Ship systems connectivity	Aircraft systems connectivity
NB-IoT	Low-bandwidth, long-range communication	Enhances connectivity and data collection in remote areas	Real-time tracking of vehicles, traffic management	Monitoring of rail systems and cargo tracking.	Supports maritime asset tracking, safety, and navigation.	Aircraft health monitoring and operational data.
LoRaWAN	long-range, low-power	Extends the coverage of digital twin networks to remote areas	Traffic flow monitoring and parking management.	Predictive maintenance and train positioning	Monitoring of vessels, cargo tracking, and safety	Aircraft maintenance

4.4.2. Challenges and opportunities of heterogenous communication

Heterogeneous communication, in the context of digital technology and networks, refers to the use of diverse and varied communication methods, protocols or technologies to transmit data and information. In other words, it involves the integration of different communication systems that may use various standards, languages or formats to exchange data. Heterogeneous communication allows for flexibility and adaptability in connecting different devices, systems or networks, even when they are not originally designed to work together. This approach is often employed to address complex and multi-faceted communication needs in modern technology environments, ensuring that various components can interact effectively, despite their differences.

The integration of heterogeneous communication systems in the context of digital twin transport presents both significant challenges and promising opportunities. While the utilisation of diverse communication protocols offers the advantage of flexibility and adaptability, it also introduces complexity in managing data interchange and compatibility. The challenge lies in harmonising these various communication technologies to ensure seamless data exchange between different elements of the transportation system, such as sensors, vehicles and infrastructure. Furthermore, data security and privacy concerns are paramount, particularly when information is transmitted through a mix of public and private networks. However, this heterogeneity also opens up opportunities for enhanced data coverage and accessibility, enabling a more comprehensive understanding of transportation systems. Leveraging these diverse communication avenues can enhance real-time decision-making, optimise traffic management and improve the overall efficiency of transport networks. As digital twin technology continues to evolve, addressing these challenges and maximising the benefits of heterogeneous communication will be crucial for its successful application in the realm of transportation.

4.4.3. Communication infrastructure

Essentially, the infrastructure for smart transport and digital twinning involves two major types of assets: physical and digital components. The physical components include connected vehicles and road infrastructure, while the digital aspects involve cloud-based systems for asset management, communication infrastructure and mobility-as-a-service (MaaS) apps, traffic control and EV fleet management software (Smart Mobility: Main Elements of Growing a Platform Business, 2023).

Connected mobility relies on a sophisticated infrastructure that integrates various technologies to enhance transportation systems (New Mobility, n.d.). This translates to a network of connected road infrastructure, connected tunnels (Providing Equitable Convenient Transit with the LA Metro Regional Connector, n.d.), connected traffic, connected marine transport, connected logistics, connected rails and connected airports (Integrated Airports, n.d.). Central to this infrastructure are high-speed communication networks, including 5G and vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, facilitating real-time data exchange. The current infrastructure for communication technologies in digital twins for transportation modes primarily relies on established networks such as 3G, 4G and 5G, as well as specialised protocols like LoRaWAN and NBIoT. These technologies enable real-time data exchange, remote monitoring and the creation of virtual representations of physical assets, enhancing the efficiency, safety and sustainability of transportation systems. However, future infrastructure is expected to witness significant advancements. This includes further adoption of 5G and upcoming 6G networks, which offer even higher speeds and lower latency, making them ideal for autonomous vehicles and complex traffic management. Many products, including automobiles, now include a high degree of sensor and data communication capabilities as standard features ("Digital Twins in Logistics - a DHL Perspective on the Impact of Digital Twins on the Logistics Industry," n.d.). Already, almost 50% of all new vehicles sold globally are connected, meaning they can communicate with other systems over networks (4G/5G, wireless, GPS) and/or via sensors (Bluetooth, NFC, RFID) (Smith, 2022). By 2030, 95% of newly sold vehicles will include communication services and 45% will have intermediate or advanced levels of connectivity (Bertoncello et al., 2021). Additionally, the integration of edge computing, blockchain for enhanced security, and the expansion of IoT ecosystems will contribute to more agile and sophisticated communication infrastructures, ensuring that digital twins continue to drive innovation and efficiency in the transportation industry. IoT devices and sensors, distributed throughout vehicles and infrastructure, collect data on traffic flow, vehicle conditions and environmental parameters, enabling real-time monitoring and analysis. The storage and processing of this vast amount of data occurs in data centres and cloud-based platforms, providing valuable insights for traffic management and predictive maintenance. Geospatial and mapping services ensure accurate location-based data for navigation and traffic control. Additionally, smart infrastructure elements, such as adaptive traffic lights and road signs, enhance traffic management. Cybersecurity measures are essential to protect data and system integrity. User interfaces, mobile apps and dashboards empower commuters with real-time information and decision-making capabilities, while environmental sensors contribute to sustainability efforts. As EVs become more prevalent, the ubiquity of EV charging stations is integral to maintaining the operational efficiency of electric transportation. These stations themselves provide an additional connected infrastructure network capable of contributing to the datasets for digital twins. Moreover, connected vehicles and autonomous vehicles are key components of the infrastructure, relying on these technologies to operate safely and efficiently. Public transportation systems, including buses and trains, are also integrated, enhancing overall transit efficiency. The dynamic nature of connected mobility or smart transport infrastructure ensures that it continues to evolve, driven by technological advancements and the demand for efficient, sustainable and secure transportation systems.

4.5. Interoperability

Interoperability of sensors in transport digital twins is crucial for seamless data integration and accurate visualisation. It ensures that diverse sensors, regardless of their types or manufacturers, can work together to provide a comprehensive view of the environment and transportation systems, leading to more effective decision-making and planning. A semi-formal definition of interoperability is provided by the Data Interoperability Standard Consortium (*What Is "Data Interoperability?,"* n.d.). Data interoperability addresses the ability of systems and services that create, exchange and consume data to have clear, shared expectations for the contents, context and meaning of that data (Castro, 2021). For example, a measurement of outdoor air temperature in Manchester should be understood in the same way as a measurement of outdoor air temperature in Birmingham. This translates into agreeing on a set of terms or a vocabulary whose elements have a specific meaning that is shared across multiple and diverse stakeholders like data providers, brokers, data consumers etc. (*Metadata, Data Models and Interoperability*, n.d.). In the context of the smart city or smart transport, interoperability with legacy networks and infrastructures is perhaps the greatest challenge that network planning must deal with (Song et al., 2017). This is significant as it entails more than full compliance with various networking standards. The legacy networks are not an issue by themselves, yet linking them with the smart city network backbone may entail validation of technology prior to network integration, and this may pose problems regarding interoperability and data security. When dealing with integration and interoperability, there are even more challenges than just integrating harmoniously between a smart city and the outside world. The concept of data portability, as introduced through the General Data Protection Regulation (GDPR), includes requirements for common technical standards (Wikipedia Contributors, 2019). This is to facilitate the transfer from one data controller to another, thus promoting interoperability (Carpenter & Pyles, 2011). There is a need to develop widely accepted standards to simplify the development and implementation of city models and gain the benefits of time, cost and error reduction (Shahat et al., 2021). Currently, this lack of standards and interoperability is a significant limitation as only a small number of urban digital twins can share data with other cities or organisations. Interoperability should be considered at physical level (e.g., standardised handling), organisational level (e.g., inter-organisational protocols) and business level (e.g., business models with shared value) and digital level (Pan et al., 2019). Apart from interoperability issues, urban digital twins suffer from other technical problems, the most relevant being data quality issues and the lack of computing resources to analyse in real time all the data a city can generate.

4.6. System architecture

4.6.1. Considerations for deploying sensors and IoT devices

When incorporating sensors and IoT devices into a transport digital twin, it is essential to take several factors into account (meShare, 2023). These include where and how the sensors are positioned; ensuring data security; providing a stable power source; assessing data transmission capabilities; and finally shifting regulations (Nolle, 2019). Attending to these aspects is critical for building a dependable digital twin capable of accurately modelling and enhancing transport systems. State management for digital twins involves keeping track of the condition and other details of physical devices. This includes information about the device itself, like its temperature, location and any operational issue it might currently have. It also covers how the sensors and actors on the device are configured, like their settings and limits. A useful representation of this state in a digital twin should show different views: one that displays the latest data sent to the system, another that shows the desired settings for the sensors and actors, and a live view that tells you what is happening right now (Swart, 2017). The best practices for creating and managing digital twins of IoT devices typically include considerations such as how to define objectives, choosing a platform, designing a model, implementing a solution, and monitoring and updating the digital twin (Dave, 2023).

4.6.2. Architecture

Very recently, a few digital twin studies have been conducted in the transportation domain. An analytical description of a digital twin architecture reference model for the cloud-based cyber-physical systems (C2PS), where every physical thing accompanies a hosted cyber thing in the cloud, was proposed where analytical models of the key properties of the C2PS, computation, communication and control is provided (Wang et al., 2018). System architectures for dedicated segments of the digital twin are also emerging, such as for driver intention prediction for traffic congestion avoidance (Kumar et al., 2018), and digital behavioural twins for safe connected cars (Chen et al., 2018). A holistic framework connecting various transport entities (i.e., human, vehicle and traffic) together is still rare.

A transport digital twin framework has been proposed recently (in the USA), which is defined as an AI-based data-driven cloud-edge-device framework for transport services.[Error! Bookmark not defined.] Some characteristics of this architecture for digital twins include scalability for high computing power, facilitation of data sharing, streamlining of microservice deployment, and the support of easy extension to new transport services.

A comprehensive architecture for a large-scale transport digital twin is yet to emerge. However, an illustrative design for the transport digital twin concept combines cloud computing and edge computing, facilitating both real-time and bulk-batch handling, processing and analysis of transport/mobility data. As depicted in Figure 10, the architecture can be categorised into four tiers:

1. the device layer, responsible for data generation and the consumption of guidance
2. the edge layer, which includes computing, communication, and storage components
3. the API (Application Programming Interface) layer, linking the cloud layer to external APIs
4. the cloud layer, constructed on AWS and its virtual private cloud (VPC) infrastructure

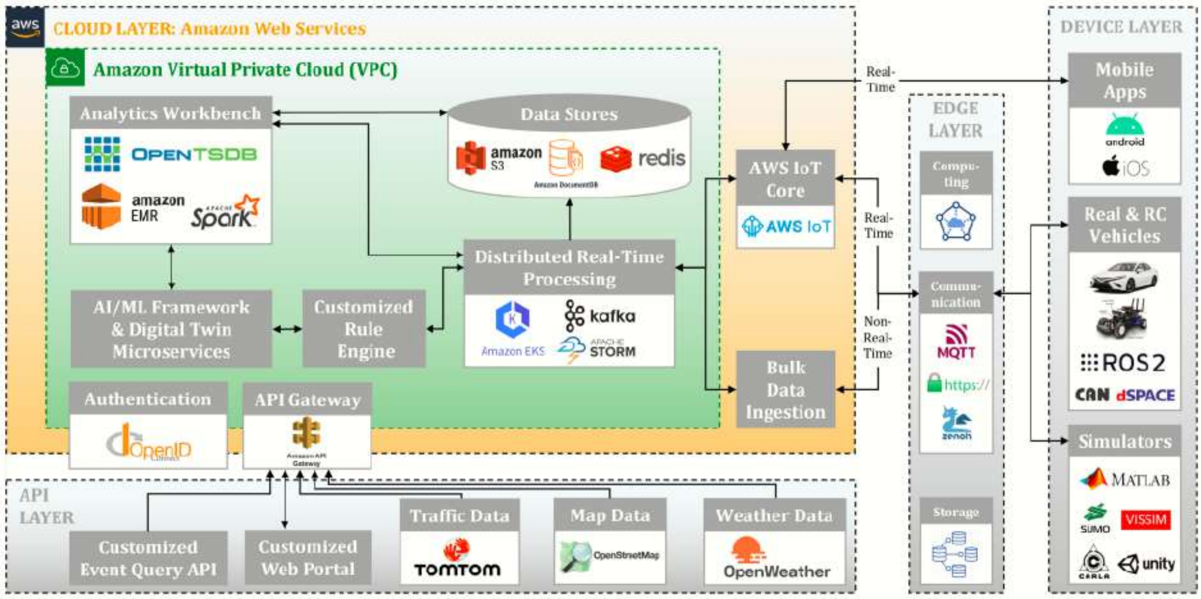

Figure 10. Example architecture of the proposed transport digital twin, with the cloud layer, edge layer, device layer and API layer (Wang et al., 2022)

In Figure *10*, the specific technologies used are just one or more examples, and so in reality more options remain both possible and emerging, with the prospect of integration of technologies between digital twin subsystems in a larger and wider transport digital twin.

4.7. Sensor data: uses, quality, reliability, and security aspects

A digital twin of even a small segment of a system may use many sensors with a wide variety of digital outputs. Thus, within a small component or subsystem of a transport digital twin, a large amount of data can be generated and transmitted across the system architecture. Given that this communication may be in real time or near real time, high throughput of data translates into the need for a reliable network and high data bandwidth at high speeds. Below, in order to highlight some of the requirements, we provide some example scenarios.

4.7.1. Data uses

Aircrafts typically employ about 5,000 sensors, which together create an astounding amount of data, 10 GB/s per engine. That is 1002 GB/s, or 2.04 Tbps for a typical twin engine such as an Airbus 320NEO or Boeing 737MAX. For comparison, a Formula 1 car produces around 1.2 GB/s, and the current batch of P&W plane engines collects data in low megabits, not terabits per second (Valich, 2015). A condition monitoring system on ships uses special sensors (such as temperature, vibration and pressure sensors) to check if the ship's parts are working well or showing signs of problems (Lag et al., 2015). These sensors record data on the ship and then send it to a data centre on land for analysis. Some companies have already made these systems, like ESRG's OstiaEdge Monitoring suite (ESRG Releases OstiaEdge Monitoring, 2009). Major names in ship machinery, such as Rolls-Royce, Wärtsila and ABB, are also making their own systems. Moreover, Rolls-Royce offers a 'Power by the Hour' service for aviation, and this is also a consideration for maritime (Rolls-Royce Celebrates 50th Anniversary of Power-By-The-Hour, 2012); the idea is to help ship owners manage the care of their ships and learn how to make better products. Some research projects are working on the data and rules needed for these systems in the maritime world but it is important to make sure the data is accurate and safe from mistakes or problems. This needs new data skills, along with what people traditionally know about ship operations. It has been estimated that a typical car on the road can produce 25 Gb of data per hour – note that this is from a single car (Fowler, 2019). Thus, in a connected car scenario and in the case of autonomous or semi-autonomous vehicles, the amount of car-generated data will be significantly higher than this figure because of more sensor used and more communication between cars happening. Similarly, trains also produce a huge amount of data, e.g., a line pattern recognition system captures around 10 TB of image data alone every 440 miles or roughly in 4-5 hours, and thus only image data produced is at the rate of over 2 TB/s (*New Measurement Train (NMT)*, n.d.). How much of this data is transmitted and how much can be transmitted in real time in a digital twins scenario? This remains a key consideration.

4.7.2. Data quality and reliability

Essential aspects of sensor quality and reliability include sensor cost, sensor quality information, data frequency, streaming features and sensor life span. Data quality is considered crucial for the digital twin (Henderson, 2022). Quality and reliability concerns need to be considered regarding event triggers, sensor calibration, sensor drift and external feedback. Automated checks may be used to identify outliers and predict invalid data points (Automatic Outlier Detection - Hydrosphere.io, n.d.) . However, the definition of quality and reliability constraints can be complex and may require human intervention (Guidance on the AI Auditing Framework Draft Guidance for Consultation 20200214 Version 1.0 2 AI Auditing Framework -Draft Guidance for Consultation, 2020). Sensor calibration, such as for air quality sensors, often involves periodic recalibration using high-precision reference stations, which helps enhance data accuracy and fosters collaboration with manufacturers. Feedback from the user community through various channels can be gathered by larger user organisations, while individual sensor maintenance can be the focus of smaller organisations to ensure data quality is maintained across the twin network. Efforts to establish unified API standards aim to enhance data accessibility across observatories. 'Birmingham Urban Observatory (BUO)' leads in implementing these standards (Hamed et al., 2022). Key considerations for API architecture development include standardised vocabulary and versioned APIs for agile development (Middleton, 2023). A common data download format, or a set of unified data formats, will be helpful in maintaining the data quality and reliability across the twin network and in the interpretation and visualisation of the data sets across the network.

4.7.3. Reliability of data communication

Often a vehicle will face challenges that are primarily linked to outdoor environmental conditions (Fong et al., 2003) and travel speeds (Wang et al., 2008) . While the latter parameter is theoretically controllable, adjusting a vehicle's speed for better communications quality remains unfeasible in practice. Therefore, any wireless communication system supporting vehicular communication must ensure uninterrupted connectivity as vehicles travel at real-world speeds, which can exceed 100 mph (160 km/h) in many countries. Here, the transition from High-Speed Downlink Packet Access (HSDPA) (3G) to Long-Term Evolution (LTE) (4G) networks offers a notable advantage as LTE employs the Orthogonal Frequency Division Multiplexing (OFDM) transmission scheme, known for its robustness against frequency-selective fading. In general, 4G/5G and newer networks can maintain connections at typical vehicle travel speeds, with swift handovers between nearby base stations.

4.8. Gaps

Building on the ground we have covered in the preceding sections and considering the current state of knowledge and research in this area, a number of gaps and suggested areas for research can be identified:

- As far as the role of sensor elements or sensor systems for digital twins is concerned, a plethora of cutting-edge options are already commercially available, and more are being developed in the context of IoT-enabled sensors. However, IoT sensing is relatively new and is currently a largely unregulated space. As such, care must be taken when analysing data or purchasing equipment. As sensors are deployed in the field, they can suffer mechanical and electrical breakdown, communication issues and degradation over time.

- Increasingly data is seen as a saleable commodity and clients can be locked into proprietary systems. Pursuing an open, scalable, and amalgamated solution to enable data for all and the public good would be ideal.
- The emerging development of hydrogen technologies in the case of large transport solutions, such as trains, freight and buses, should afford opportunities to develop novel sensing solutions for this part of the transport sector.
- While there are many other opportunities for new sensor and sensor system development, perhaps the greatest area, ripe for development, remains in building resilience into the system solutions and architecture for digital twins. The breakdown of the UK Air Traffic control system in September 2023 was revealed to be due to a "rare event" of 1 in 15 million due to faulty data input. Still, it resulted in thousands of passengers being stranded abroad for days after 1,500 flights were cancelled during one of the busiest travel periods of the year, with costs estimated at £100 million.[52]
- System architecture for digital twins of segments of the transportation network remain in their infancy. Design for large-scale (smart city scale) transportation digital twin can still appear to be a distant prospect.
- There are universal concerns regarding data size, quality and reliability which may be reduced with the use of news standards and protocols, and which remain partially dependent of system design as well as the integration of the evolving communications infrastructure. Of course, cybersecurity (discussed in detail in Chapter 6) remains a fundamental concern throughout the solution architecture.
- As of now, the focus of digital twin development seems to be on better traffic management and adding value to the operational efficiency, or in cost improvement, and more recently decarbonisation (O'Brien, 2023).
- There may be other opportunities beyond the immediate business as usual that need to be explored and identified which can add further value and may even open new business solutions and services. Logistics is one such sector which may be more receptive to new solutions.
- There is a need for comprehensive strategies and models to harness the full potential of diverse data sources for transportation system optimisation. A research gap lies in the limited exploration of how heterogeneous communication sources in transportation systems can be effectively integrated and leveraged through digital twin technology to enhance real-time decision-making, traffic management and overall network efficiency.

5. WP4 Digital infrastructure components for transport digital twins

Cities, transport authorities and government departments have access to a vast amount of data sources, offering a huge array of insights to be revealed and harnessed. The economic value embedded within this data (TRIB, Digital Twin Roadmap 2035) can be unlocked through the concept and development of digital twins for mobility and transport systems, and this brings with it the potential to transform how transport systems operate, whether that is change through decarbonisation, cost reduction, efficiency, better decision-making or innovation.

The foundation of digital twin technology is data, which is the media by which digital twins understand, respond and interact with the real world (Weifei, 2021). The success of any digital twin project hinges on robust methods and standards of data collection, management, secure storage, interoperability and effective integration. These elements will require developers and their stakeholders to establish a common language, adopt consistent approaches and implement comprehensive frameworks.

It is essential to strike a balance between data collection and environmental impact, ensuring that the benefits of data-driven transportation improvements outweigh the energy consumption associated with data processing.

In this section, the roles of data and digital infrastructure in transport digital twins will be explored, describing how these components come together to develop and deploy digital infrastructure for transportation and looking at the state-of-the-art technology across the principle area of activity.

5.1. Key data requirements for transport digital twins

Transport digital twins rely on the intelligent integration and management of data from a multitude of sources. This section will therefore present an overview of the main data requirements for transport digital twins, their key characteristics, technology challenges and considerations.

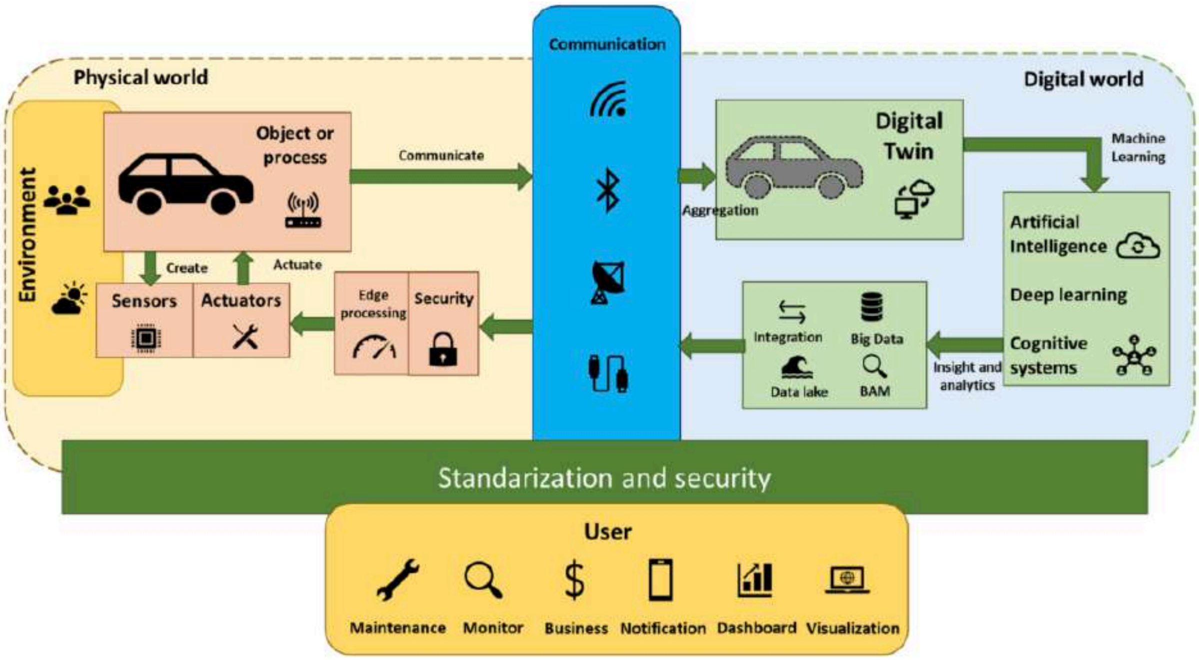

Figure 11.Digital twin architecture

The foundation of a successful transport digital twin lies in its ability to aggregate data from diverse sources, using this data to simulate, analyse and optimise many areas of transportation. This section will explore the role of data sources in building and operating one.

Cities and government bodies have a huge wealth of possible **data sources** which can include (Chapman, 202?): geospatial data for mapping and navigation of transport systems; environmental data to understand the impact of transportation; infrastructure monitoring to monitor the safety and efficiency of transport systems; traffic monitoring to optimise traffic flow and reduce congestion; public transport data; vehicle data to understand traffic patterns; historical data to analyse trends and aid with future planning; and administrative & policy data

Data comes in various types and **formats**, each serving a specific purpose for monitoring and modelling transportation systems. A selection of the main data types essential for transport digital twins, and their key characteristics, would include:

- data format: can be structured, such as numerical sensor readings; semi-structured, such as JSON feed from IoT devices; and unstructured, such as images or video streams
- real-time and historical data for planning and decision-making
- geospatial information for routing, mapping and navigation.
- multimodal data for various transportation modes (e.g., road, rail, air, maritime) in data analysis
- big data processing, vast amounts of data are generated

However, it must be borne in mind that these data types bring with them a number of **challenges and considerations**, such as challenges related to protecting sensitive transportation data, issues with data reliability and accuracy, which can impact decision-making, difficulties in integrating and sharing data from multiple sources and mode and an absence of standardised data formats and protocols. There are also considerations such as citizen accessibility and equity or the 'digital divide', where not everyone can easily access transportation data (Attaran, 2023).

As transport digital twins continuously collect and process data from a multitude of sources, the **volume of data** generated is vast. The implications of this data volume and their potential growth are significant.

Connected vehicles, sensors and monitoring devices contribute significantly to the increasing data volumes in the transportation sector. For example, some connected cars produce over 25GB of data every hour. It is expected that these data volumes could grow to 100 petabytes per month in the future (Statistica, 2017). The handling of petabytes of data presents a significant computational challenge in terms of transmission, bandwidth, storage and management. High-performance computing resources for data analysis are required to manage these vast amounts of data.

Effective and optimised **data management** is a fundamental consideration of transport digital twins, which rely on a robust framework for data management to ensure their functionality, efficiency and effectiveness. This is essential for collecting, processing and making informed decisions based on the vast volumes of data generated by transport and infrastructure systems.

Data management in transport digital twins has many aspects that must be perfomed successfully. Transport digital twins gather massive volumes of data from diverse sources, such as sensors, cameras, vehicles and infrastructure monitoring systems. The collection of this data along with the efficient storage requires a robust and efficient management framework and methods so that datasets can be processed and analysed efficiently and effectively. This will include techniques such as data cleaning, aggregation and transformation to glean insight and valuable information.

The transport digital twin management framework must also support the creation and maintenance of models and the continuous real-time data integration to ensure that the transport digital twin remains up-to-date.

The digital infrastructure must also address how to balance different needs such as performance, latency, cost-efficiency, data privacy and security.

The digital infrastructure must also be scalable to adapt to changing data volumes and evolving requirements over time.

The key challenges and considerations regarding data requirements and management are summarised below and then explored in more depth throughout the chapter:

- data quality and accuracy: issues may arise with the reliability and accuracy of data, such as ensuring the correct calibration, missing data points, sensor drift. Incorrect data or models can impact decision-making
- data privacy and security: sensitive transportation data may require stringent protection measures such as GDPR compliance
- data integration: integrating data from diverse sources and modes requires standardised processes and systems
- data handling: efficient data handling and processing
- data storage: suitable storage infrastructure must be in place to accommodate multiple, massive datasets
- data processing: advanced data processing techniques, such as big data analytics, are necessary to gather insights from large volumes of data
- real-time analysis: transport digital twins need to handle and analyse data in real-time to support decision-making
- scalability: the digital infrastructure must be scalable to adapt to increasing data loads
- lack of standardisation: the absence of standardised data formats and protocols can impact interoperability
- accessibility and equity: the digital divide can affect access to transportation data

5.2. Data security

The opportunities provided by the vast amount of data gathered by transport digital twins are offset by security and privacy risks which must be mitigated. Transportation systems collect and process sensitive data, including real-time location information, personal traveller data and critical infrastructure details. Ensuring the confidentiality, integrity and availability of this data is essential for maintaining the trust of the public, regulators and other stakeholders.

Cybersecurity in relation to transport digital twins is discussed in more detail in the following chapter. However, considerations and best practice for data security are noted here and effective data security policies must be implemented by design during the development of transport digital twins.

The key challenges and areas of consideration in terms of data security are data encryption, access control, authentication and data anonymisation.

5.3. Data storage

Data storage facilities are fundamental components in enabling the effective use of vast and diverse datasets within digital twin platforms. The selection and architecture of storage solutions are critical to accommodate the scalability requirements and relationships between the data elements. This section will explore the various storage options available, their respective advantages and disadvantages, key characteristics, existing technology challenges and identified gaps.

A digital twin platform requires the integration of multiple datasets, robust data storage solutions and a well-designed architecture. These components are essential not only to handle the volume of data generated but also to effectively manage the complex structures and relationships inherent in digital twins. (Natarajan, 2023).

There are vast computation and storage needs due to the large datasets generated with IoT devices, the complexity of 3D models and rendering. Extremely efficient computation is required in fields such as autonomous driving. However, challenges such as latency persist in these applications (Ferre-Bigorra, 2022).

The following high-level requirements define the main components and architecture (Wilmes, 2023):

- storage for growing amounts of high frequency time series data
- low latency queries against specific time ranges of data, large ranges of data retrieval and data aggregations
- hierarchical data structures for components, subsets, models
- version control to track changes and ensure data consistency within dynamic structures and models
- statistics at the macroscopic scale to gather insights from vast datasets

Cloud computing involves the delivery of computing resources, such as data storage, processing power and software over the internet (Weil, 2023), and is defined by the National Institute of Standards and Technology (NIST) as follows (NIST, 2011):

“Cloud computing is a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (for example, networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. The definition is summarised in the figure below and it comprises of five essential characteristics (on-demand self-service), broad network access, resource pooling, rapid elasticity and measured service), three service models (software as a service, platform as a service, and infrastructure as a service), and four deployment models (public, private, community and hybrid).”

Its advantages for enterprises and other organisation include scalability options and pay-as-you-go pricing models available. Challenges, on the other hand, include the costs associated with large-scale projects along with security and privacy concerns (Knebel, 2023). Figure 12 highlights the main cloud computing characteristics and models.

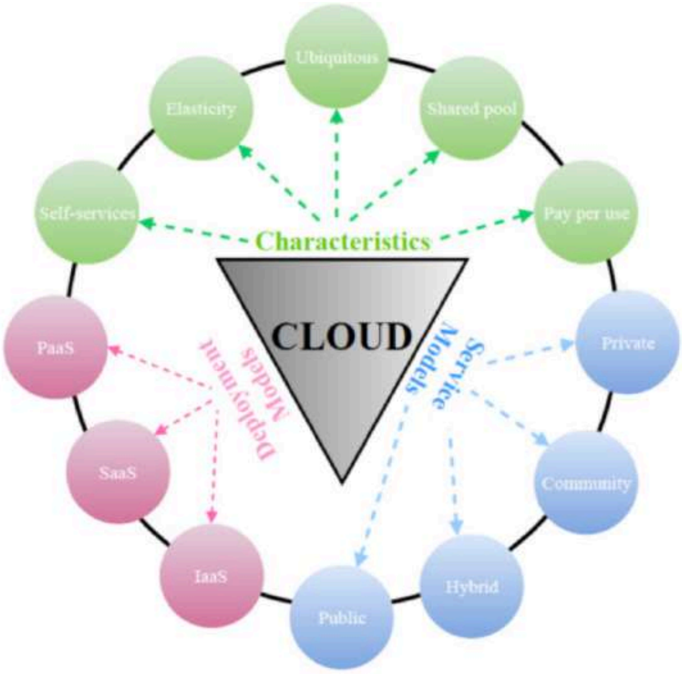

Figure 12.Cloud computing characteristics and models

The emergence of commercial cloud computing services such as Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform, has greatly facilitated the development of many applications in the domain of transportation cyber-physical systems. These services provide a variety of technical infrastructure and building blocks for analytics and distributed computing.

As an example of a typical cloud computing service, AWS, which has the largest market share (32%) among all competitors in 2023 (AAG, 2023), comprises over 200 products and services for computing, storage, networking, database, analytics, IoT, computer vision, machine learning, security and more. As well as providing scalability, these cloud computing services provide the capacity to offload data and computing demands effectively.

A cloud platform must be trustworthy and secure to deploy and analyse data. The nature of public cloud platforms means that the provider companies inevitably have control of the data resources to some extent, which could introduce cyber security and privacy risks for end-users (Wang, 2022).

A **private cloud platform**, on the other hand, consists of cloud computing resources used exclusively by one business or organisation. Since the services and infrastructure are always maintained on a private network, a private cloud platform can address the security and privacy issues faced by a public cloud platform. Private cloud platforms also make it easier for end-users to customise cloud resources to meet specific requirements.

Although private cloud platforms are more secure and flexible, there are several disadvantages compared to public cloud platforms, for example they are typically more expensive, due to the dedicated infrastructure created for a particular organisation. Additionally, they are often outperformed in terms of scalability and reliability by public cloud platforms, which provide on-demand resources and a vast network of servers to mitigate against failures. The cost-effectiveness of services varies based on specific requirements and configurations.

On-premise storage involves an organisation running its own IT infrastructure and software applications within its own facilities, rather than using a third-party provider.

The advantages of this include having more control over the IT infrastructure and data security and customisation of the system to specific needs. However, on-premise storage can be expensive to set up and maintain and may not offer the same scalability as cloud computing.

Edge storage refers to processing data closer to the source of the data, such as the sensor or camera, rather than in a centralised data centre or cloud.

This reduces the amount of data that needs to be transmitted, which can improve the responsiveness and latency of applications, making this a solution suitable for real-time applications such as autonomous vehicles. Edge storage can also be a cost-effective solution.

However, the challenges around edge storage can include limited capacity, complex management and maintenance requirements and potential data security issues (Knebel, 2023).

Cluster computing involves the interconnected operation of multiple computers to function as a single system. It can deliver increased processing power and storage availability, along with scalability and fault-tolerance.

However, it can be expensive to set up and maintain clusters, and issues related to data consistency and coordination between the different computing nodes can also cause challenges.

In considering and comparing data storage solutions, it is important to understand and take into account some of the key characteristics across the different options, notably:

- Scalability: digital twins generate massive volumes of high-frequency time series data. The storage solution must accommodate the growing data influx efficiently.
- Low latency: some applications, like autonomous vehicles, demand extremely low latency for real-time decision-making. Storage systems should support rapid data retrieval and processing.
- Hierarchical structures: data in digital twin platforms often exhibit hierarchical relationships. Storage systems should support the organisation of data into components, subsets and models for ease of access and analysis.
- Version control: maintaining versioned structures and models is essential for tracking changes and ensuring data consistency in dynamic digital twin environments.
- Macroscopic scale statistics: analytics and statistical analysis at a macroscopic scale are crucial for gaining insights into large datasets.
- Data security: ensuring data security is vital. Encryption, access controls, and threat detection mechanisms need continuous improvement.
- Interoperability: ensuring that different digital twin components and systems can interoperate seamlessly is a critical challenge. Standards and protocols for data exchange need to be established and adopted.

With these characteristics in mind, a summary of data storage types presented, their advantages and challenges is provided in Table 11 .

Table 11.Comparison of data storage types

Storage Type	Description	Advantages	Challenges
Cloud storage services	Commercial cloud computing services (e.g., AWS, Azure, Google Cloud)	Scalable nature Variety of technical infrastructure Offload data and computing demands	Costs of large-scale projects

Public cloud platform	Trustworthy, but introduces potential cybersecurity and privacy risks for end users	Scalability Cost-effectiveness for on-demand resources	Less control over data resources Potential data privacy concerns
Private cloud platform	Exclusively used by one business or organisation	Enhanced security and privacy Customisation of resources	More expensive set-up and maintenance Lack of scalability compared to public cloud Cost-effectiveness varies with specific configuration
On-premise storage	Running IT infrastructure and software within an organisation's own facilities	Full control over IT infrastructure Customisation of the system Data security	Expensive setup and maintenance Limited scalability compared to cloud
Edge storage	Processing data closer to the source (e.g., sensor or camera) instead of central data centre or cloud	Reduced data transmission Improved responsiveness and latency Suitable for real-time applications	Limited capacity Complex management and maintenance Potential data security issues
Cluster computing	Interconnected operation of multiple computers functioning as a single system	Increased processing power Scalability Fault tolerance	Expensive setup and maintenance Data consistency and coordination issues

As digital twin technology evolves, **innovations in data storage solutions** will be vital in addressing existing challenges in managing and utilising vast and complex datasets. A selection of latest developments in storage solutions are summarised.

Blockchain technology is being explored as a method to enhance data security, integrity and transparency in digital twin platforms. Through the use of decentralised ledgers, data can be securely recorded and verified at each stage of its lifecycle. This not only ensures data authenticity but also facilitates secure data sharing and traceability in multi-stakeholder transport environments (Raj, 2021).

Data compression techniques can encode, re-structure or modify data files with the aim of reducing their size, while **data deduplication** can eliminate data repetition and redundancy, thereby reducing the storage overhead requirements. These techniques can significantly reduce storage footprint, which becomes increasingly important where large datasets are constantly generated and stored; transmit data more quickly over networks, reducing latency for real-time data requirements; and optimise resource allocation, improving overall system performance.

Data management processes can be automated by **AI-driven** or machine learning techniques. These techniques can intelligently categorise, index and retrieve data, making it easier for users to access relevant information quickly and efficiently. AI can also be used to predict storage needs and optimise resource allocation (Davenport, 2022).

Hybrid cloud-edge architectures are being developed as a solution which combines both cloud and edge storage. These architectures integrate edge devices with cloud resources, allowing data to be processed locally when needed for low latency and transmitted to the cloud for storage, analysis and long-term archiving. This approach can minimise network bandwidth usage, reduce communication latencies and take advantage of processing resources on smart devices to reduce the burden on servers, therefore maximising flexibility and efficiency (Alamouti, 2022).

5.4. Standardisation & interoperability

A transport digital twin is an encapsulation of all the relevant data generated by vehicles, infrastructure and users for management and optimisation contexts. One major issue for transport digital twin implementation is interoperability, or the ability of two or more systems, components or processes to exchange contextualised information so that they can act on this information to achieve better operational decisions and prediction outcomes (Weil et al, 2023).

Transport digital twins require a data ecosystem that is diverse, interoperable, accessible, inclusive and secure. The current infrastructures lack interoperability in the context of urban digital twins. It has been proposed that it is the most pressing unresolved issue regarding urban digital twins (Ferré-Bigorra et al., 2022).

There is therefore a requirement to develop a series of standardised data formats, methodologies and regulations which address issues such as data sharing, data privacy and ethical considerations.

A collaborative effort from a global community with a commitment to advance transport digital twin technology is required. This section will discuss the main challenges, opportunities and gaps in these areas, while highlighting some of the ongoing initiatives, committees and working groups currently addressing these challenges (Chester, 2021).

- Next Generation Service Interfaces (NGSI-LD) is an information model and API for publishing, querying and subscribing to context information. It is meant to facilitate the open exchange and sharing of structured information between different stakeholders.
- Smart Data Models provide standardised data models related to the smart cities domain.
- SC41 of ISO/IECJTC1 was renamed as the sub-technical committee on the internet of things and digital twins, and the WG6 working group was established.
- The industrial internet consortium contains working groups on digital transformation, edge computing, technology and special interest groups, to carry out research on digital twin technology and to promote the development of related standards.
- The Open Geospatial Consortium offers a suite of open standards intended to be of use to urban digital twins, many of which will be applicable to transport digital twins: CityGML, IndoorGML, SensorThings, 3DTiles, i3S and OGC API standards.
- The Open Geospatial Consortium also defines the Geographic Markup Language (GML) which serves as a modelling language for geographic systems as well as an open interchange format for geographic transactions.
- The Geospatially Enabled Ecosystem for Europe (GeoE3) is an initiative focusing on how sustainable development can be supported on the basis of easily accessible digital information, by exemplifying how a platform of data services can be built. The GeoE3 data platform can integrate high-quality datasets and services with geospatial data from existing national geospatial platforms, providing users with meaningful analyses and visualisations of complex issues.

Although transport digital twin technology has gained momentum during the past decade, there is no universal definition of this technology, let alone existing standardisation. Currently, the joint 'IoT and

Digital Twin' technical committee of the ISO and the IEC is still developing the standards for the digital twin in terms of concepts and terminology, as well as use cases (Wang, 2022).

5.5. Analytics tools

Since large amounts of multi-source, heterogeneous data is generated during the operation of a digital twin, big data analytics technologies are required to collect, transmit, store and process the data (Weifei, 2021).

Analytics in the context of digital twins involves the computational processing of stored and/or received data and information. Typically, this will involve either interrogation and investigation of data from and about the physical entity and its environment, or comparison of observed/collected data with outputs from simulations.

Analytics tools are used to analyse the behaviour, performance and operation of the physical entity. The analysis may be based on historic and/or current operational and environmental data based on projections of future demand (Weifei, 2021).

Figure 13 shows many of the main features of digital twins, using big data and machine learning approaches.

Big data analytics can be divided into the following aspects: analytic visualisations, data mining algorithms and predictive analytic capabilities.

- means. Data can be visualised by different forms of tables and graphics such as histograms, bar charts, pie charts, etc.
- Data mining refers to the process of algorithmically searching for information that is hidden in a large amount of data. A typical task within data mining is classification. Classification analysis identifies and assigns categories to a collection of data to allow for more accurate analysis. The classification method makes use of techniques such as decision trees, linear programming, neural network and statistics.
- Predictive analytics is the process of using data to forecast future outcomes. The process uses data analysis, machine learning and statistical models to find patterns that might predict future behaviour.
- Analytic visualisations aim to communicate clearly and effectively with the aid of graphical

Sharma et al. (2022) discuss the application of machine learning and big data in digital twins. They suggest that real-time machine learning analytics are an essential component of digital twins, as one of the main uses of a digital twin is to be able to reliably and accurately output how a physical asset or system will behave in conditions which have not arisen yet, using the real-time data it is receiving. Additionally, machine learning in digital twins is to predict and anticipate an impending problem which may need timely attention and intervention.
For transport digital twins, the ability to forecast and address dynamic conditions and potential issues in real-time is a critical component for efficiency, safety and sustainability of transportation systems.

Machine learning models can be used for a digital twin to learn and adapt in real-time, by providing feedback to both the physical asset or system and to the digital twin model itself.

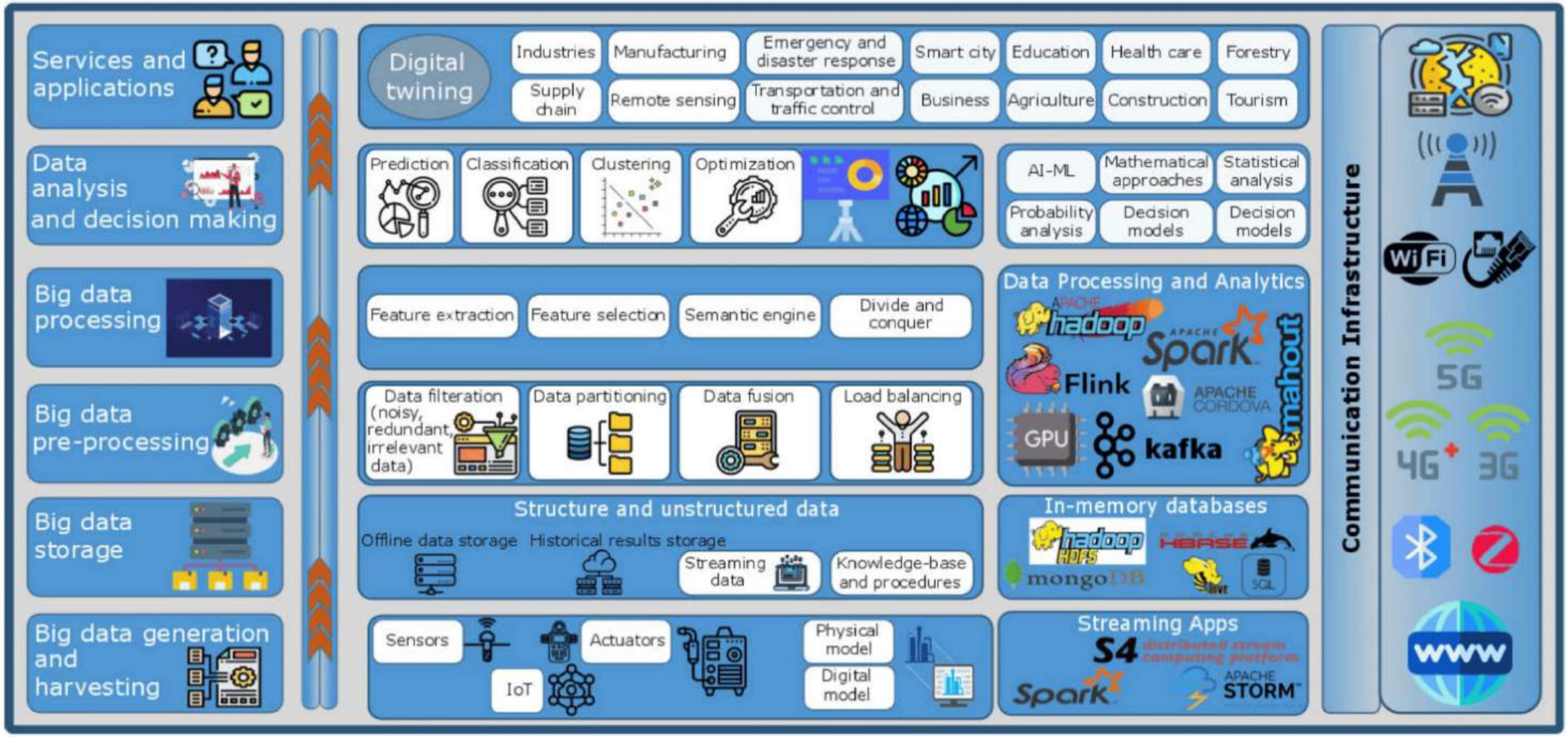

Figure 13.Features of digital twins using big data and machine learning approaches

5.6. Big data solutions

As multisource, massive, heterogeneous data are generated during the operation of vehicles and transport infrastructure, big data technologies are required to collect, transmit, store and process the data. Big data solutions represent an innovative and critical development in the operation of transport digital twins, where they offer a combination of data analytics and digital representation to enable intelligent decision-making and understanding of complex transportation systems.

Big data solutions combine characteristics such as real-time data collection, predictive modelling and scalability, key aspects of the challenges of designing and running transport digital twins.

The following table is a selection of big data solutions for data storage, management and processing. Their suitability for transport digital twins is noted along with their limitations.

Table 12.Big data solutions and their suitability for digital twins

Technology	Overview	Suitability for digital twins	Limitations
Apache Hadoop	Open-source framework for distributed storage and processing of large datasets	Batch processing and historical data storage for digital twins	Not suitable for real-time analytics, complexity in setup and management
Apache Spark	Open-source distributed data processing framework	Suitable for both batch and real-time analytics in digital twins	Learning curve, resource-intensive real-time processing
Apache Flink	Open-source stream processing framework with low-latency and high-throughput support.	Well-suited for real-time analytics, especially in streaming data	Complex setup compared to batch-oriented frameworks, not as mature as Spark or Hadoop for some use cases.
Apache Kafka	Distributed streaming platform for real-time data ingestion, processing and messaging	Crucial for ingesting and processing real-time data in digital twins	Focus on data streaming and messaging, may require other platforms for analytics

Technology	Overview	Suitability for digital twins	Limitations
Apache Mahout	Open-source machine learning library with scalable algorithms for machine learning tasks	Implementing machine learning models in digital twins for predictive analytics	Limited ecosystem compared to other machine learning libraries, may not cover the latest deep learning advancements

Assessing the suitability of big data solutions for transport digital twins is of key importance to allow suitable data-driven insights and efficient operation.

5.7. Visualisation tools

Visualisation tools are an essential aspect for the development analysis and usage of digital twins, enabling stakeholders to gain insights, make informed decisions and optimise transportation systems. A selection of key visualisation tools and technologies commonly used in digital twin development is provided below.

- **GIS software** like ArcGIS, QGIS and MapInfo allows for the mapping and visualisation of transportation infrastructure, including roads, railways and public transit systems. These tools are fundamental for location-based analysis and planning.
- **3D modelling** tools such as Autodesk AutoCAD, SketchUp and Blender can be used to create 3D representations of transport infrastructure and vehicles.
- **Simulation tools** such as AnyLogic, Simulink, and VISSIM enable the creation of dynamic, real-time simulations of transportation systems. They help in modelling traffic flows, traffic planning, optimising routes, addressing congestion and emissions challenges, and testing scenarios for different modes of transport.
- **VR and AR technologies**, along with tools such as Unity and Unreal Engine, offer immersive visualisation experiences. These technologies are valuable for training, safety analysis and public engagement, allowing users to interact with a digital twin.
- **Dashboards and data visualisation** tools like Tableau, Power BI and D3.js are used to create interactive dashboards and data visualisations. They help in presenting real-time data related to transportation such as traffic conditions, vehicle locations and energy consumption.
- **IoT dashboards** are a requirement to monitor sensors and devices in the transport network. Specialised tools such as Grafana and ThingsBoard can be used, providing real-time insights into sensor data, enabling proactive decision-making.

- **Computer-aided design (CAD)** software and **BIM** tools like Revit and Bentley MicroStation can be used for detailed modelling of infrastructure and buildings which can be integrated into the digital twin.

- **Mobile apps and web interfaces** are key tools for making digital twin information accessible to a wider audience, including commuters and government officials. They can provide on-the-go access to real-time transportation data.

One example of a technology study for advanced visualisation of digital twins is investigated by Holliman et al (2019). Their objective was to create a scalable cloud supercomputer software architecture for photo-realistic terapixel 3D visualisation of urban IoT data, supporting daily updates, using the public cloud. An evaluation of cloud supercomputing for their application was performed and key lessons from the terapixel project were that the cloud can deliver world class supercomputing performance at reasonable cost and that future cloud supercomputing projects would benefit from system improvements including: better metrics collection, performance visualisation modules, transparent error reporting and simpler purchasing, licensing and cost tracking systems.

5.8. Computing power

The implementation of a transport digital twin relies on the performance capabilities of the computing platform. Real-time performance is a critical requirement for the effective running of transport digital twins. To achieve this, an approach towards optimising the data and algorithm structures to improve task execution speed is necessary. Several important considerations play a role, including the overall performance of the computing platform, the time delay of the data transmission network, the capacity of the cloud computing platform and the design of optimal computing architecture to meet real-time analysis demands (Yao et al., 2023). The computing capability of the system is the foundation of the entire transport digital twin.

With the increasing scale of high-performance and cloud computing, the computational sciences are susceptible to having silent and unintended environmental impacts. The sector of information and communication technologies (ICT) was responsible for between 1.8-2.8% of global GHG emissions in 2020 – more than aviation (1.9%) – and, if unchecked, the ICT carbon footprint could grow exponentially in coming years (Lannelongue, 2023).

To address these challenges, research is underway to find methods to reduce the energy needs of computing power and transport digital twins.

Arslan A., et al. (2018) propose an energy-efficient high-performance computing approach based on field programmable gate arrays (**FPGAs**) which can provide comparable computational resources to CPUs and GPUS, yet require much lower amounts of energy per operation. They recommend that FPGAs are preferred resources to reduce both energy supply and cooling costs in the data centres that will be needed by smart cities. In their paper, they describe efficient implementations of high-performance algorithms that can process traffic camera image sequences to provide traffic flow information in real-time at a low energy and power cost.

The field of environmentally sustainable computational science (ESCS) is relatively new with many opportunities to explore (Lannelongue, 2023).

Continuous improvements in processing efficiency have been made through the development of new hardware, building lower-energy data centres and implementing more efficient high-performance computing systems.

In addition to the environmental effects of electricity usage, manufacturing and disposal of hardware, there are also concerns around data centres' water usage and land footprint. Computational science and AI have the potential to facilitate low-carbon urban mobility, therefore it follows that the tools and processes themselves must be exemplary in their sustainable energy practices (Lannelongue, 2023). The environmental impacts of an innovation must be outweighed by its environmental and social benefits.

An emerging discipline at the intersection of climate science, software design, electricity markets, hardware and data centre design, **green software** refers to carbon-efficient software, meaning it emits the least carbon possible in its creation, energy use and storage.

The Green Software Foundation states that the following areas are key for being a green software (Green Software Foundation).

The Green Algorithms project aims at promoting more environmentally sustainable computational science and provides tools and toolkits for researchers to use to estimate the carbon footprint of project. While aimed at researchers, the calculator is included as an example of developments in this area (Green Algorithms).

5.9. High-volume data and de-carbonisation

Intelligent traffic management systems, as well as solving problems such as improving traffic flow and safety, need to be able to solve problems such as reducing air pollution, making traffic more efficient, reducing fuel consumption, and making other modes of transport, such as public transport, cycling, or car-pooling, more attractive (Zhihan, 2023).

High-volume data traffic generated by sensors, cameras and IoT devices in transport systems provides **real-time insights** into traffic conditions, vehicle performance and emissions. This data can be used to help decarbonisation efforts by enabling real-time monitoring and optimisation of transport systems. For instance, it can be used to optimise traffic flow, reduce congestion and improve fuel efficiency.

Data-driven **traffic management** strategies, such as adaptive traffic signal control and dynamic route optimisation, can help reduce idling times and fuel consumption, thus lowering emissions. [Ref]

High-volume data traffic can be used to manage and optimise **EV charging infrastructure**, predict EV charging demand, and provide remote monitoring. The deployment of renewable electricity and electric vehicles presents a synergistic opportunity to accelerate the decarbonisation of power and transport sectors (Zhihan, 2023).

Data from sensors on vehicles and infrastructure can enable **predictive maintenance**, reducing downtime and improving the energy efficiency of transportation systems.

High-quality data can support initiatives to encourage **mode shifts**, such as promoting public transportation, cycling or car-pooling, or for modifying road user behaviour in response to changes in the road environment, e.g. reducing speed limits, changing traffic signal phases or lane closures (ITS Master Plan, Mainroads Western Australia).

Neves & Brand (2019) conducted an in-depth observational study of 50 residents in Cardiff, Wales, to assess the potential for carbon emissions savings from replacing short car trips with walking and cycling. Their results showed that active travel has enormous potential to replace short distance car travel, with a considerable impact on the carbon footprint of a personal journey.

Fleet operators can use data to **optimise routes**, reduce vehicle idling and vehicle maintenance to increase fuel efficiency. The transition to electric or hybrid vehicle fleets can also be guided by data on vehicle performance and energy consumption (Kaklis et al., 2023).

The **logistics industry** can use high-volume, real-time data to view an entire freight ecosystem. This data can be used to develop sustainable logistics and optimise freight movement through enhancing resource allocation, optimising routes and reducing empty miles (Botin-Sanabria,. Et al., 2022)

High-volume data traffic and analysis allow for detailed **environmental impact assessments** of transportation projects, helping policy-makers make informed decisions about infrastructure investments and developments.

Open data can be used to create transparency about emissions and environmental impact, raising **public awareness** and encouraging citizens to make greener transportation choices.

High-volume data and decarbonisation strategies in relation to transport digital twins could define a pivotal shift in future transportation. Real-time data, modelling and monitoring traffic movement, logistics, environment and infrastructure allows for multifaceted challenges to be addressed – whether to reduce air pollution through enhancing traffic efficiency; optimise electric vehicle charging infrastructure; promote more eco-friendly modes of transportation; or minimise fuel consumption.

By the development of innovative, intelligent transport management systems and transport digital twins, possibilities are opened for more informed policy decisions, encouraging environmentally conscious choices for the individual and ecologically responsible decisions by national and global government bodies and companies.

5.10. Key challenge areas

Key areas requiring research and development that have been identified throughout this chapter on digital infrastructure are:

1. Investigate methods to enhance data quality and accuracy, addressing issues related to calibration, missing data points and sensor drift.
2. Develop robust data security methods for transportation systems to ensure the confidentiality and integrity of sensitive data such as real-time location information, personal traveller data and details regarding the critical infrastructure.
3. Research efficient data management frameworks for optimising data handling and storage techniques such as compression and de-duplication.
4. Develop advanced and efficient data processing techniques to handle and analyse large amounts of data in real-time.
5. Develop standardised data formats and protocols for effective data integration and enhanced interoperability.
6. Investigate methods to efficiently combine disparate, heterogeneous data sources in transport digital twins.
7. Develop methods to estimate storage needs for transport digital twins depending on factors such as data retention, data variety, data granularity, data redundancy and scale of deployment – city-wide, regional, national.
8. Develop methods to estimate the computing power necessary to run a transport digital twin, depending on factors such as data volume, data complexity, spatial and temporal resolution and scale of deployment – city-wide, regional, national.

9. Build collaborative groups and communities, facilitate ongoing engagement between government, private sector, public utilities, building owners, community groups and citizens.
10. Capture and share best practices and lessons learned from digital twin case studies globally.

6. WP5 Transport digital twins and cybersecurity

Cyber security and resilience are essential factors in the development, deployment, operation, maintenance and decommissioning of internet-connected systems. Lack of planning, design and implementation of suitable policies, procedures and protocols to address these factors, creates a fundamental risk of manipulation of these systems. The resultant effects on cyber-physical systems may be unwanted behaviours, loss of data, or impacts on the physical integrity of assets and safety of users.

The adoption of a "secure by design" approach by industry for cyber-physical systems can be argued to be an enabler for organisations delivering tangible products or services, including those to the general public. The closer scrutiny of an organisation's own processes, products and services from a security standpoint could also lead to an improvement of their overall design, functionality and, potentially, productivity. Furthermore, the visibility of adopting this approach can build greater trust and confidence within an organisation, its stakeholders and customers. In the context of the decarbonisation of transport, adopting common best practices may enhance the cohesiveness of joint activities and reduce perceived barriers to the adoption of technology and interoperability. In doing so, this should help enable the development of deployable solutions at scale for the ecosystem.

Digital twinning approaches are now seen as part of the digital transformation plans for many sectors (Erol et al., 2020) (Attaran & Gokhan Celik, 2023). Digital twinning architectures' reliance on IoT technologies, cloud computing infrastructure and applications delivered as services, require cyber security and resilience to be addressed. However, at the genesis of what we now refer to as a digital twin, the maturity of associated cyber security best practices and standards were not uniform across these enabling technologies.

As discussed in Chapter 2 (2.1.), the concept for digital twinning was publicly used in 2002 by Michael Grieves at a Society of Manufacturing Engineers event in the US, in reference to product lifecycle management. This was three years after the term 'Internet of Things' was first used by Kevin Ashton, and in the same year Amazon established its subsidiary Amazon Web Services. However, the terms 'IoT' and 'digital twin' were not in active public use until around 2008-2010, after which greater use and adoption occurred. It was not until 2019 that the first globally applicable standard for consumer IoT security was launched by the European Telecommunications Standards Institute (ETSI). Prior to this date, cyber security-related aspects had been incorporated in other sectors or application-specific standards and generally with a focus on machine-to-machine (M2M) communications.

References in current literature to digital twin cyber security typically refer to the use of digital twins to test the cyber security of a device, subsystem, system or process. This is in contrast to that of the security or resilience of the twin itself. Gartner believes that the rise of digital twins coincides with the rise of IoT (Hippold, 2019), yet development of a systems approach to cyber security to meet the specific needs of digital twins and networks of digital twins is still at a relatively early stage compared to the technologies it consists of, such as IoT.

6.1. Application of Cyber security and resilience principles

To understand the potential for the application of cyber security and resilience principles to digital twins and networks of digital twins, it useful to understand the sectors they emerged from.

As an evolution occurred from digital models to digital shadows and then digital twins, it was evident that aerospace and then manufacturing were the two sectors operating as early adopters. This was primarily due to a twinning approach providing a suitable means to virtually test and validate physical systems and processes. This was achieved through simulation and emulation, which would otherwise be physically challenging and costly due to the extremes of the environments in which the physical devices, systems and processes operate. Testing and validating physical devices, subsystems and systems in situ for these sectors is often not possible while they are in operation, due to the effects on their functionality and that of the other systems they integrate with. Both aerospace and manufacturing share a similar characteristic in that they are both regulated, in contrast to some general applications in the built environment space, which may be less regulated. This is also true of the emerging use of digital twins in the medical space.

Aerospace, manufacturing and medical sectors' regulations, including cyber security, have meant that previous digital twin implementations have been very siloed. The applications of twinning methodologies developed in regulated sectors to other sectors and applications, such as those in intelligent transport networks, will need more than just minor modifications due to the diversity of environments, systems and actors. This is particularly the case with the wider range of cyber security and resilience risks, due to less controllable operating environments.

Large-scale intelligent transport networks and the decarbonisation of these networks present several challenges for the application of current cyber-physical security and resilience principles to a digital twin or network of twins. These include:

- the existing legacy infrastructure, which is not connected to the Internet, i.e. it is unable to access live data
- the large number of public, private and third-sector partners involved
- the magnitude and range of parameters involved in modelling aspects of
    - offline data to real-time data
    - generation and ingestion of event-based data, data at periodic intervals, and condition-based data
    - the influence of the natural environment, such as geography and weather systems
    - the need to model human factors at, in some cases individual, as well as group level
- the need to potentially model both objects and processes from inception to decommissioning, i.e. over the full lifecycle
- the wide range of standards and legislation that already exist in the different sectors
- the constant evolution of the modelled environment
- the wide range of required uses of the twins from R&D and integration testing to strategic planning, infrastructure and asset management, and end-of-life assessments
- the threats posed through the ease of access to elements of the network, including physical attacks
- the limitations and threats of using 'black box' technology from overseas suppliers

In summary, the challenge is a cross-sectoral, multi-scale, multi-level, multi-temporal and multi-domain cyber-physical challenge. The cyber security and resilience challenge inherits issues not only from using the constituent enabling technologies, but also from the new challenges in aggregate. Fundamentally, digital twins' cyber risk comes from the two-way interconnection between the virtual representation and the physical real-world asset or system. This provides attackers with options for exploiting attack vectors in either the cyber domain or physical domains to potentially affect both domains. It is this enlarged attack surface that makes digital twin networks more difficult to secure than, for example, a single-purpose IoT system.

Examples of potential cyber-physical attacks on digital twins include:

- Reconnaissance attacks: an attacker gathers intelligence by scanning networks to find vulnerabilities or by introducing malware. Once a vulnerability is found, the attacker may use the twin as an entry point to move deeper through the connected networks. This is referred to as lateral movement.

- Digital twins mode (select) attacks: an attacker considers the operation modes of digital twins. A replication mode attack could record an event in a 'real' system and replay the event to elicit a response in the digital twin. Alternatively, in a simulation mode attack different inputs are provided to a simulation of the twin in an isolated virtual environment. This allows the attacker to learn how to manipulate the real digital twin to get the response they require. The better the digital twin's representation of the physical system, the more effective the attack may be.

- Victimising physical systems or twin or both: an attacker targets either part or both parts, with the aim of collecting data or damaging the physical system. It is possible that the attack may reside in either or both parts for a prolonged period of time These are referred to as an advanced persistent threat (APT). Kulik et al. (2022) also state the purpose of an attack on a twin may be to slow down communications between the digital twin and physical counterpart. It also seems feasible that an attack may increase computation in the digital twin to limit the simulation processes, hence slowing a key process within the twin and reducing the ability to make timely predictions or control decisions. (Suhail et al., 2023)

The resultant risks can generally be classified as: theft of data, corruption of data undermining trust, or to elicit a specific response (data poisoning), temporarily reducing the functionality of the physical system or the digital twin counterpart or causing permanent damage. These risks may also compromise safety.

Examples of documented cyber-attacks on the underlying technologies used in digital twins are common (Langner, 2011) (Kolias et al., 2017) (Goldbaum & Rashbaum, 2021); however, for digital twins themselves, outside of academic research, they are scarce. It is reasonable to theorise that this is due to several factors: the limited number of large-scale operational digital twins, the number of digital twins that are recognised as such, and potentially the limited interest in reporting incidences.

However, one public example of an 'attack' was on the well-known digital twin, Google Maps which provides access to mapping and navigational services across many countries. Google receives the location and speed of movement of every smartphone that uses Google Maps and uses this information to provide the best route to your destination. It can also use historical information to predict journey times for future dates. This feedback to users can then affect the utilisation of part of the road network, potentially directing traffic to use routes not intended for heavy usage. In 2020, artist Simon Weckert demonstrated how loading a hand-pulled cart containing 99 smartphones and walking through the streets of Berlin could confuse Google Maps into thinking there was a traffic jam, when none was present. Google admitted that it could not filter out that type of activity (Barrett, 2020). While itself not trying to cause disruption, the incident demonstrates that relatively simple 'attacks' could easily elicit changes to a transport-focussed digital twin. In the case of Weckert's demonstration, it may have routed traffic to use other less suitable routes for motorised vehicles.

It could be argued that given the multi-dimensional aspects of a digital twin, traditional approaches of a one-off risk assessment during a development cycle are insufficient to guarantee secure and resilient operation over its lifecycle. As the digital twin evolves, the risk assessment must too, by factoring in changes in configuration or modes of operation of the digital twin and its physical counterpart, and new and emerging threats. In doing so, an evaluation of the effect on both the probability and impacts of the risk occurring must be completed. As a result, new or improved mitigating actions may be required.

6.2. Emerging approaches, frameworks, best practice and standards

In the cyber security and resilience research literature, activities seem to predominately target the underlying technologies used to construct a digital twin, rather than the twin as a system of systems. Implementing a digital twin of a network of twins without considering system-level cyber security and resilience would be unwise. Given the complex nature of digital twins, new emergent threats may only be detected and mitigated if a system-of-systems approach is adopted. This was assumed as part of the National Digital Twin (NDT) programme, delivered by the Centre for Digital Built Britain.

In 2018, the Gemini Principles were published, with the aim to propose principles to guide the NDT programme and its enabling information management framework. The fourth principle was 'Security', with a key aim that the NDT and supporting framework "must enable security and be secure themselves" (*The Gemini Principles*, 2018) and the NDT must be 'secure by design', i.e. address security principles from the outset. These included protection of personal data and privacy, sensitive national infrastructure assets, commercial interests, and intellectual property. In addition, risks arising from data aggregation must be mitigated.

In 2021, 'The pathway towards an Information Management Framework (IMF)' was published, based on the Gemini Principles. The aim of the IMF was to enable secure data-sharing and effective information management, a core requirement for digital twinning at scale. This would bring together both standards and data exchange protocols, enabling the creation of an ecosystem of connected digital twins (*The pathway towards an Information Management Framework, 2021*). According to the planned assessment of security threats and approaches, it was deemed necessary to extend beyond concepts of confidentiality, integrity and availability when considering security issues. The additional concepts were:

- authenticity of data/information
- utility: over the lifecycle of an asset it will change, and this requires the management of data to ensure that at any given time, it is comparable and consistent with historic data of the asset
- safety: the safety case for the asset, its use or outputs when changes occur to the physical and digital elements of the digital twin
- resilience: the ability to recover from adverse events
- control: the ability to control unauthorised access and modification of the physical elements of the digital twin
- sensitive information: the protection of personal data and privacy, sensitive national infrastructure assets, commercial interests, and intellectual property (*The pathway towards an Information Management Framework, 2021*)

Adoption of frameworks such as the IMF requires its translation into practical implementable steps that can be taken by organisations and a method for measuring the ability of the organisation to meet the aims of the frameworks, i.e. a maturity model.

As IoT is a crucial part of a digital twin, and in order to assist solution developers to understand what risks must be considered when integrating into a digital twin, the Industry IoT Consortium and Digital Twin Consortium created a white paper, providing a 'Digital Twin Profile for their IoT Security Maturity Model' (SMM) (*IoT Security Maturity Model Digital Twin Profile, 2022*). The model considers both single digital twin and federated digital twins with an architecture as shown in Figure 14.

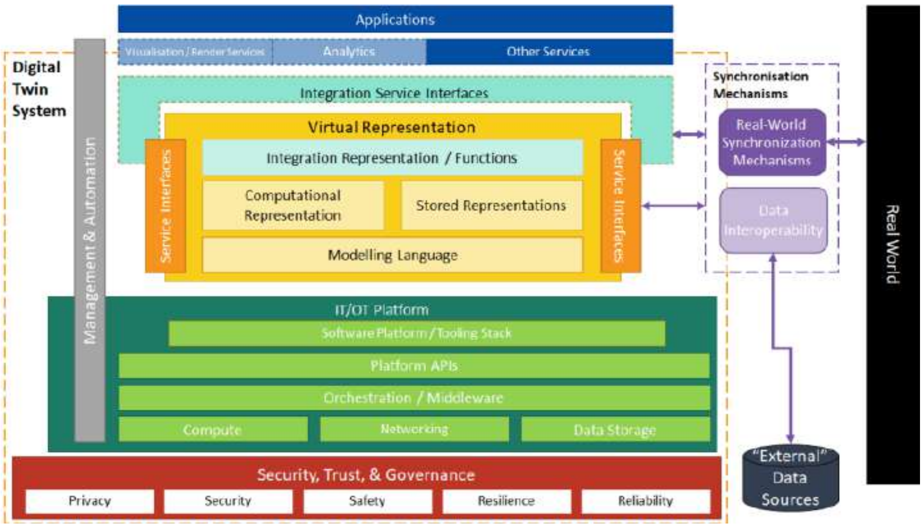

Figure 14 Digital twin architecture
Source: IoT Security Maturity Model Digital Twin Profile, 2022

In the SMM, 18 practice tables are presented, each one covering different practices (such as Compliance Management and Threat Modelling) in three categories: governance, enablement, and hardening; there are also system-specific scope considerations at different comprehensiveness levels: minimum, ad hoc, consistent, and formalised. This is one example of a model that can be applied to digital twins irrespective of the application, including intelligent transport systems and energy systems.

In Alcaraz & Lopez (2022), the authors make a strong case for the need to create models for IoT, citing the security issues created by IoT given its critical role in automation processes, and the fact that digital twins contain intellectual property, which represents a digital copy of a physical asset or system. An exploration of security approaches is provided which is broader in scope to the SMM and includes:

- hardware and software security
- hardening of DT infrastructures
- identity, authentication and authorisation
- deception, intrusion detection and situational awareness
- response and recovery
- event management and information sharing
- trust management
- governance and security management
- traceability, auditing and accountability
- training and the human aspects

Within this list of approaches, it is clear to see that both technical and non-technical approaches should be considered. The authors also state that it is necessary to undertake new research devoted to how digital twins can be used to enhance the protection of critical infrastructures.

More generally, there is discussion that digital twins, while presenting additional cyber security risks, themselves can be used to improve cyber security maturity (Eckhart & Ekelhart, 2019). Jafari et al.(2023) state that the use of digital twin technologies in smart grid and transportation applications provides a key benefit of reducing the time to detect and respond to physical and cyber-attacks. In the paper, various academic projects are identified that address particular risks through the use of digital twin-based machine learning techniques, based on convolutional neural network (CNNs), generative adversarial networks (GANs) and long short-term memory network (LSTM) approaches. While digital twin operating states and the environment of the physical counterpart may change, and are flagged as challenges, the authors states that the use of deep learning and reinforcement learning technique should form part of effective strategies to address these. An example of these technologies being adopted is Lupovis, a Scottish university spin-out supported by CENSIS. Lupovis creates virtual decoys of physical Internet-connected systems and deceives attackers into thinking they are attacking the 'real' system. This not only diverts the attacker, but can also be used to slow their progress and learn about their attack techniques, thus enabling the enhancement of the 'real' system to be resilient to that threat.

While sharing common underpinnings, digital twins are currently more evident in the literature for energy systems than transport systems. Examples of national activities include the Virtual Energy System programme by the National Grid (*Virtual Energy System Programme Strategy,2022*), the Energy Systems Catapult's Energy System Digital Twin Demonstrator (*BEIS Energy System Digital Twin Demonstrator, 2022*, and the recently launched collaborative R&D project ENSIGN: ENergy System dIGital twiN led by University of Strathclyde (University of Strathclyde, 2023). The latter Prosperity Partnership project's aim is the development of a digital twin architecture using AI and machine learning methods to understand whole energy systems by integrating multiple energy vectors. Despite the seemingly greater number of publications covering digital twinning in energy systems, there is still a lack of detail in regard to practical cyber security and resilience specifically for digital twins beyond following best practices for the underlying technologies.

Standardisation is an important process for ensuring that multiple parties can conform to an agreed set of rules, guidelines or characteristics. Currently there is no all-encompassing international standard for digital twins; however, in the past couple of years there have been attempts to explore how existing standards may enable this to be addressed (*First report on standards relevant for digital twins*, 2021), (*Considerations for Digital Twin Technology and Emerging Standards, 2021*) (Wang et al., 2022). There are more than 10 bodies currently working on developing standards for digital twins including the IEEE, ETSI, ISO and IEC. There are many more if we look at organisations developing standards for enabling technologies used in digital twins, particularly given specific standards in different market verticals, e.g., manufacturing (*Automation systems and integration – Digital twin framework for manufacturing, 2021*) *(International Standard for Digital Twins, 2020*) and built environment (*Built environment. Digital twins overview and principles, 2022*) (Organization and digitization of information, 2020).

From a cyber security standpoint there are existing standards, directives and legislation that are likely to affect development and roll-out of digital twins in the UK. For IoT this includes:

- ETSI EN 303 645 Cyber Security for Consumer Internet of Things: Baseline Requirements
- ISO/IEC 27000 series for Information Security
- NIS2 Security of Networks & Information Systems

- GDPR
- the Product Security and Telecommunications Infrastructure Act 2022

As IoT does not operate in a silo, other technology-focussed standards are likely to apply, e.g., for operational technologies, the ISA/IEC 62443 series covering Automation and Control Systems cyber security standards. Similar standards for the other enabling technologies exist and when factoring- n standards for specific technology applications, a potentially large matrix will be formed. Some of these standards will not be in direct relation to the digital twin itself but may need to be factored into the simulation of system of systems if a fine level of detail is virtually replicated for processes in these. For example, a transport services application mapped into a digital twin may need to factor in security of information in relation to the collection and transmission of credit card information, in which case the payment card industry data security standard (PCI DSS) will be applicable. It is feasible that non-UK specific standards and legislation may need to be taken into account if system functionality is affected as a result of meeting these by design. In the case of data being exchanged outwith the jurisdiction of the UK, additional standards and legislation may apply.

At the time of writing, there is no holistic standard for cyber security and resilience for digital twins aimed at decarbonisation in whole transport systems. Nor is there a clear mapping of existing standards to digital twins in this area.

6.3. Existing gaps in digital twin cyber-physical security

Given the relative immaturity of the application of 'true' digital twins and networks of digital twins to large-scale, real-world applications there are several areas of recommended research. These are as follows:

- Undertake a detailed mapping of standards and regulations for digital twinning for decarbonisation of transport – this is required to understand areas of compliance for both cyber and physical aspects given the wide range of sectors, technologies and processes. Aspects of cyber physical security, resilience, privacy and trust are likely to be embedded in existing standards and regulations; however, this mapping will highlight opportunities to innovate and contribute to existing bodies undertaking activities in this space. For example, ISO/IEC's JTC 1/SC 41/Working Group 6 specifically focuses on digital twin standardisation, including related technologies of digital twins. The result of this mapping may be the need for the development of a specific standard and/or framework focussed on secure decarbonisation of transport systems.
- Research into cyber physical security and resilience for networks of digital twins in which these systems of systems may exhibit different behaviours and present additional risks to the underlying enabling technologies.
- Specifically address the challenge of assessing and preserving the veracity of data exchanged between digital twins and also between twins and their associated physical counterparts, as a means to aid adoption and build trust in the use of digital twins. This may also need to look at the ingestion of data from questionable sources, e.g., third-party sensors. Aspects of the management of shared and open data exchange should be explored, along with techniques for preserving privacy.
- Explore the management of security, resilience and privacy responsibility across multi-domain cyber physical systems involving evolving digital twins. Investigate if an automated process can be implemented to flag areas of joint responsibility or areas where responsibility is unclear.
- Research how unusual events, such as emergencies, may need to be addressed by trading off aspects of security in order to enable a more rapid response in a digital twin network.
- Define a secure modular digital twin architectural template and network of twins template for the decarbonisation of transport which meets the existing requirements and is extensible to address future needs, including changes in the cyber physical threat landscape.

- Research how a distributed active defence function can be designed into digital twin networks which can adjust to rapidly evolving threats through techniques such as federated learning.
- Research how the risks of design, operation and maintenance of digital twins by human can be mitigated, e.g., error checking, integration validation and automated insider threat assessment and detection.
- Contribute to the mapping of the skills required to train a new generation of professionals to understand the complexity of building secure digital twins connected to wider cyber physical systems. This may result in the development of both college and university-level curriculums and CPD courses for upskilling the existing workforce. This is likely to require both an understanding of the operation of transport and energy systems and technologies including IoT and sensor systems, cloud computing, machine learning/AI, simulation/emulation and visualisation. This area may be a good candidate for a Centre for Doctoral Training.

7. WP6 Transport digital twins – case studies

This chapter provides case studies to illustrate the profound impact of digital twins on the transport industry, showcasing how these virtual replicas are reshaping the way we design, monitor and optimise transportation systems for a more sustainable and connected future. The broad spread of real-world examples provided presents the practical applications, benefits and challenges of digital twins in transport, highlighting their role in enhancing efficiency and sustainability.

To provide a comprehensive view of digital twin applications in the transport sector, the case studies encompass a variety of transportation modes, and include examples from large-scale mobility in smart cities, logistics (transit of goods), railways, aviation, maritime and, to complete the picture, the energy sector. The selected case studies are geographically diverse in order to showcase how digital twin technology is being implemented in different regions and in various socio-economic contexts. This diversity also helps highlight the versatility of digital twins in addressing transport-related challenges.

The primary criteria used for selecting case studies has been availability of data and transparency in reporting. Case studies with accessible data, detailed methodologies and clear documentation of outcomes are preferable as they allow for more in-depth analysis and verification of results, although it must be acknowledged that the level of data transparency and clarity on methodology varies. Case studies are presented in a standardised manner in order to show similarities between digital twin systems but also to underscore differences, be it in the technology maturity level or the scale. Each case study explains the problem a digital twin solution is being used to address and how the digital twin was designed and performed, i.e., how data was collected and how it was processed.

As mentioned above, the case studies presented here vary in terms of the scale and maturity of the digital twin technology. Some focus on a single component, like a proof of concept (PoC) on rail switches (see Case study 5), or on a very specific task, like data modelling in the aviation industry for cabin retrofit (Case study 4), or a simulation of air cargo loading (Case study 3), or on the complex management involved an incident management system in a smart city (Case study 2). The case studies also showcase the diversity of understanding of what a digital twin is. Following the definition provided in Chapter 2 (2.1.), not all case studies comply with the characteristics of a digital twin. As in Case studies 4 and 6, they present necessary steps towards the realisation of a fully functioning digital twin, with data modelling and deep learning technique being one of these. This allows for a nuanced understanding of how digital twins can be applied at different scales and what 'background work' this requires.

Each section begins with an overview of a specific transport sector, before moving onto individual case studies for that sector. This overview presents success stories but also shows where challenges have arisen. This provides insights into the potential benefits of digital twins, as well as the obstacles practitioners may encounter when implementing them.

The first 'sector' presented is the smart city, followed by logistics, rail, energy networks and maritime.

7.1. Smart city – Large-scale urban mobility operating system

The large-scale urban mobility system is a crucial element in the smart city landscape. It is a comprehensive and integrated platform designed to address the complex transportation and mobility challenges that arise in densely populated urban areas. Ideally, it works as a central hub for integrating various modes of transportation and mobility services, including public transport, bike-sharing, e-scooters and more.

The smart city is an excellent ecosystem in which to implement ‘federated/integrated’ digital twin systems. In this context, the smart city can be defined as a system of systems, “consisting of multiple, heterogeneous, distributed components that can interact and exchange information across a large-scale network”(Wolf et al., 2022). Massive transport systems leverage advanced data analytics and real-time data from sensors, GPS devices and other sources to monitor traffic flow, congestion and demand patterns. This data-driven approach helps to optimise transportation routes and services. By achieving multi-layer optimisation of the city traffic, transport digital twins in smart cities contribute to a reduction in GHG emissions and air pollution (He et al., 2022).

It is worth noting here that the concept of a smart city goes beyond mobility services. It encompasses the critical city infrastructure, such as water supply, waste disposal, lighting and of course, urban transport networks, but also the quality of services, public safety and comfort of living. In that regard, the digital twin can be utilised in emergency operations to manage the incident response processes (see Case study 2 - Incident management in a smart city).

The large implementation scale of digital twin technologies for transport/mobility is essential to make the most out of digital twins: to achieve the optimisation of city assets, increase efficiency, cost reductions, and so on, but also to generate extensive operational picture and diverse observation points to inform and stimulate policy-making. Digital twins are an excellent platform to experiment with different policies, but also to safeguard transparency among all stakeholders related to mobility services in a city (Yeon et al., 2023).

The development of digital twins must take into account the dynamic and static aspects of the data on which they are based, as well as the need for 2D and 3D representations of situations and environments. High demands must be placed on the visualisation quality, as this has a direct influence on the usability of the twin (human interpretation). However, as AI keeps evolving, the need for visualisation might lessen as the AI will overtake the data interpretation. Data streaming must be very fluid, visualisation of vehicle movement and passenger/pedestrian behaviour must be seamless, and latency must be as low as technically possible. This brings ubiquitous connectivity to the forefront of digital twin infrastructure in a smart city.

Large metropolises are developing various smart city-related solutions, including digital twin systems, to manage the vast urban infrastructure and diverse services, but also to monitor various environmental parameters (e.g., GHG, black carbon).

A good example is Singapore, that appears to be emerging as a leader in digital twin adoption (see also the section on the Maritime sector, below). The Singapore Land Authority wanted to ensure that it effectively uses its land and space resources, and therefore initiated a national 3D mapping of Singapore via aerial and street mobile mapping. Over two phases, the project sought to map the entire region with rapid reality data capturing technologies, creating an accurate, reliable and consistent national 3D map that supports government agencies in their policy formulation, planning, operation, and risk management. For aerial mapping, the team had to conduct 3D mapping over the entire land mass within 40 days at the highest level of detail. Mobile mapping meant providing point density of 40 points per square metre and 360-degree panoramic images at 20m intervals. The team also needed to remove people or cars from all images and ensure that it captured the reality data hidden behind these objects. The Authority partnered with Bentley, applying its tools Orbit 3DM, iTwin Capture and ContextCapture. It is already known that the built digital twin increased data availability by 50%, and enabled accurate information extraction and collaborative data exchange that can be used for multiple planning purposes. It helps to avoid bottlenecks and keep traffic moving (Camus, 2023).

In China, the work on a digital twin for Shanghai is equally impressive. As reported, the digital twin of the transport system incorporates the Huangpu River, airports, ports (the Yanhgshan Port), as well as construction sites. These efforts comply with China's ambitions in its Five Year Plan (2021-2025) to deploy nationwide digital twins to improve management of urban assets and capacities (Yuting, 2022).

In Germany, the city of Stuttgart launched a collaboration with digital solutions provider Hexagon and tech company Fujitsu to develop a digital twin platform aimed at boosting sustainability, to monitor a diverse range of challenges including water quality, flood levels and parking space occupancy (Carey, 2022). The Bavarian State Ministry has launched the TwinBy programme to implement digital twin systems in various Bavarian cities such as Munich, Ingolstadt and Bamberg, to support mobility services, flood management, energy network management and road planning. All its envisaged digital twins should be operational by the end of the project, which also aims to standardise data access and data architecture.

Nothing at the operational scale of a smart city comes without challenges. Scalability is desirable but yet to be achieved. It requires an extensive physical infrastructure provided from different transport/mobility providers, including various devices, and different communication protocols and data formats. As Wolf et al. (2022) explain, the integration of diverse data streams and the requirement for real-time assessment lead to the problem of the three 'big Vs':

- Volume of real-time data can vary depending on the available data sources.
- Velocity of data streams can differ (e.g. data can arrive periodically or continuously).
- Variety can depend on the data origin, resulting in incompatible data formats.

Edge computing (i.e., processing the data 'at the edge" of a network' where sensors, actuators and/or devices operate) instead of sending the data to the cloud with the resulting time delay, can be regarded as a potential solution to these challenges.

Currently, such smart city applications are usually independent systems that run in isolation and do not exchange data across their systems with other domains. Overcoming siloed digital twin systems and opening up services such as MaaS (Mobility as a Service) are other action points toward scalability.

It is noteworthy is that the heterogeneity of inputs, formats and networks mentioned here as a challenge also, paradoxically, supports the resilience and robustness of a large-scale digital twin. Should one source of telemetry data transmission fail, the heterogeneous system can synthesise data from other sources, ensuring the accuracy of information used in decision-making. The digital twin incident management prototype presented in Case study 2 is an excellent example of leveraging multiple data streams to ensure the functionality and reliability of the incident management system.

The two case studies selected for this section illustrate the scale and complexity of a digital twin in a smart city. Case study 1 is impressive due to the number of recorded data points, while Case study 2 shows the heterogeneity of a digital twin applied in incident management scenarios.

7.1.1. Case study 1 - Seoul taxi service system

Table 13 Case study 1 - digital twin of Seoul taxi service system

WHY: THE PROBLEM	
Overview	The case study focuses on the issue of taxi shortages and increased difficulty in obtaining rides in South Korea following the Covid-19 pandemic.
Transport service/infrastructure element	Taxi service system

Spatial area	Seoul Metropolitan Area
Scale	20,000 vehicles 400,000 requests per day
Elements to consider for high-degree similarity	• The temporal and spatial characteristics of travel: such as traffic congestion, peak hours, and day-of-week and time-of-day information, the latitude and longitude coordinates of origins and destinations. • The accurate calculation of travel time between origins and destinations.
HOW: THE SOLUTION	
Overview	DTUMOS (a Digital Twin for Urban Mobility Operating System) using real-world data. The results showed that it can efficiently handle a mobility system with more than 30,000 vehicles and 200,000 passengers, and provide flexible visualisations. The computation time was calculated through a series of simulation runs on a computer with 128 GB of RAM and a 3.4 GHz processor.
What data was recorded? **How was it done?**	Model training: • Historical trip records to train the model. • The input features for training the model consist of the latitude and longitude coordinates of origins and destinations, the linear distance between origins and destinations, departure time, the day of the week, public holidays, and the administrative district of origins and destinations. • To train the model, 63,14373 [as provided in the source] samples of historical taxi pick-up and drop-off data for six months from January to June 2018 in the Seoul Metropolitan Area were used. The twin: • Supply and demand generated exactly as in reality, and user customisation (e.g., spatial and temporal randomness, increase/decrease in demand and supply). • Call requests are matched every minute with the vehicles, and the objective function is designed so that the sum of the waiting times for all passengers is minimised. • The input variables include the 'vehicle operation', containing information on the status and location of vehicles, and the "passenger', containing information on the call request time and location of passengers.
Software layer/AI/ML	Utilising deep learning techniques, an Estimated Time of Arrival (ETA) model was trained and applied to improve the accuracy and simulation speed of the DTUMOS. (A travel demand prediction model or a mode choice model to assist users in selecting transportation options can also be included in this component.)
Cloud/data storage	Microsoft Azure. All input data and simulation results were stored in Azure storage, and the ETA model is trained on Azure Machine Learning Server.
How does it work?	In the loop statement, the dispatch algorithm is utilised to match vehicles and passengers on a minute-by-minute basis. The algorithm then calculates the optimal route and estimated travel time for the matched vehicle to reach the passenger. Vehicle router and ETA models are utilised in this step. The status and location of both the vehicle and passenger are continuously updated during the loop, and the final output of the simulation is saved as an output file.

Scalability	DTUMOS can be easily applied to various cities and diverse mobility services around the world. This framework can respond to changes in various mobility services and algorithms in a flexible manner. When the city operating the mobility service or the type of objects utilising the service (e.g., passengers, goods, foods, etc.) are changed, it can be implemented simply by modifying the input data. Modules in DTUMOS are developed based on open-source software and each module is concisely classified according to its function presented in Algorithm 1. In order to show the incredible extensibility of DTUMOS, various examples are provided in various types of mobility services in different metropolitan cities. Seoul, New York and Chicago have implemented large-scale mobility services, encompassing a range of services such as depot-based delivery and many-to-many pick-up and delivery, in addition to traditional taxi services. DTUMOS can be utilised to develop a variety of operation algorithms for mobility systems, including rebalancing empty vehicles, advanced dispatch, ride-sharing algorithms, dynamic pricing, and fleet size controls.
Output	(1) Visualisation: the simulation result is built as a docker image, and a large-scale mobility system can be visualised smoothly and seamlessly through continuous communication with a cloud layer. (2) A system performance report: the results of the simulation conducted through DTUMOS indicate the optimal number of taxis that must be supplied to resolve the taxi shortage. The analysis reveals that a 20% increase in the current supply is not enough to solve the problem, and the supply must increase by approximately 50%.
Decarbonisation	Perspectives such as optimised routes travelled by taxis, less idling
Worth noting	Its lightweight and open-source nature makes it particularly useful for iterative learning methods such as reinforcement learning.
Source	(Yeon et al., 2023)

7.1.2. Case study 2 - Incident management in a smart city

Table 14 Case study 2 - digital twin prototype for incident management system

WHY: THE PROBLEM	
Overview	Design a prototype digital twin of an incident management system. Investigate how to integrate heterogeneous data between distributed multi-agency emergency systems into a common data model; how to apply processing steps to continuous real-time data streams; and how to analyse and visualise location-based incident data to enhance the understanding of the current incident environment.
Transport service/Infrastructure element	Emergency services
Spatial area	The Tyne Bridge, a critical location transport link over the River Tyne in northeast England. One incident can impact two cities at once, Newcastle upon Tyne and Gateshead.
Scale	First design and prototype of an incident response system as part of an iterative systems engineering study.
Elements to consider for high-degree similarity	• Static data: topography, buildings, administrative borders, census data including vulnerable population groups, existing hazard

	maps, and critical infrastructures such as gas, water, and electricity. • Dynamic and temporal data: incident type, scale and impact area, people involved, potential casualties, injuries and fatalities.
HOW: THE SOLUTION	
Overview	A prototype of a process digital twin that supports real-time monitoring and provides initial operational support through data information sharing and collaboration across different organisational and system boundaries. Smart city digital twin (SCDT) for disaster management and administration that enables data sensing and simulation across diverse systems.
What data was recorded? **How was it done?**	Data streams, e.g. from stationary weather stations, water gauges, traffic sensors and mobile phones. Internet-enabled devices record a series of spatial events showing the physical location through geographic coordinates (e.g., longitude and latitude), attributes describing the observation recorded, and a timestamp. Due to heterogeneous sources, incoming data may be in a structured format showing figures of impacted buildings, causalities, injuries, demographics, location-based coordinates and sensory data (temperature, humidity, wind speed, and precipitation), semi-structured or unstructured data such as multi-media data (images and videos), social media posts and online news data. Simulation of incident data (longitude and latitude coordinates and incident type) and data from first responders (longitude and latitude coordinates, responder ID and responder name) data in .geojson format.
Software layer/AI/ML	Simulation of telemetry data from a responder vehicle along a given network route using Microsoft Visual Studio, C# and the .NET framework. The Azure Maps REST API services: Data Upload, Spatial (Buffer, Closest Point, Geofence), Route Service, AccuWeather service, TomTom traffic service. Incident response system prototype developed using Azure Maps, HTML5, JavaScript, and CSS. A Microsoft Azure account is required to create and configure the Azure Maps, IoT Hub, Event Grid, Function, Blob storage and Logic Apphttps://www.nature.com/articles/s41598-022-20178-8.
Cloud/data storage	Microsoft Azure cloud computing
How does it work?	The workflow is triggered as soon as an incident occurs. The next step is to connect to internet-enabled devices and extract raw data. The data is processed, for example, by extracting the value of the measured variable, location coordinates, and the timestamp, and perform various analyses and simulations. Examples include the spatial analysis of the incident location and the route from an available responder vehicle to the incident site, including possible traffic accidents or weather hazards. The resulting outcomes are displayed visually in the form of a map. As a further step, more intelligent data insights on which they can decide action plans, notify responders and deploy resources.

	After first responders have arrived at the incident site, stakeholders can monitor whether the conditions of the incident change. Until the incident is resolved, stakeholders involved in the incident response receive updated information in a feedback loop.
Scalability	Could be reproduced in other critical interconnecting routes (e.g., Clyde Tunnel in Glasgow)
Output	Customised web application (a number of visualisations presented in the paper). Example: the web application shows the indicators: Location of incident (longitude, latitude) and buffer in metres. The map output visualises the location of the incident on the Tyne Bridge with a red marker and a red circular buffer area around the incident location.
Decarbonisation	Savings from 'shortest routes' for attending vehicles and reducing number of responding vehicles.
Worth noting	The developed use case helps to reflect on the challenges of data integration and the role of spatial data infrastructure in a multi-agency environment. The prototype developed can help to detect (near) real-time monitoring of the incident environment and work towards the user requirements. *IoT-enabled device*: A simulated ambulance vehicle equipped with an internet-enabled device to send telemetry data and further incident-relevant information. For the ambulance vehicle to send telemetry and further incident-relevant data to the IoT Hub, the device must be registered with the Azure IoT Hub. Following the device registration, the ambulance vehicle can now send simulated telemetry data from the internet-enabled device to the IoT Hub. *IoT Hub:* The IoT Hub acts as a central message hub for bidirectional communication between an IoT app and the devices it manages.
Source	(Wolf et al., 2022)

7.2. Logistics – the shipment of goods

Logistics is a complex, multi-layered and multi-stakeholder environment that is thirsty for disruptive innovation such as digital twinning. As the sector is very cost-sensitive, it is looking at novel solutions to optimise processes and routes, to improve operation efficiency or to minimise delays.

As stated in Chapter 2 (2.4.1.), the shipping industry accounts for about 80 percent of the volume of global trade in goods. As the industry continues to grow, it generates increasing carbon emissions: currently, global shipping generates 3% of worldwide GHG emissions (King, 2022). The industry is under great pressure to reduce its carbon footprint, and digital tools, particularly digital twins, facilitate this by enabling more effective route modelling and strategic planning.

Logistics providers already make extensive use of digital tools such GIS data, for example using it to plan delivery routes and predict arrival times based on weather conditions, congestion and known delays at ports, airports, and border crossings. The logistics sector has leveraged sensors to track shipments and more recently machinery and material-handling equipment. It is already common practice to ship sensitive, high-value products, such as pharmaceuticals and delicate electronic components, with sensors that monitor temperature, package orientation, shock and vibration. Today the industry is also increasingly embracing open API strategies and migrating to cloud-based IT systems. Companies are applying machine learning and advanced analytics techniques to optimise their supply chains and draw new insights from historical shipment and operational data. Logistics professionals are even implementing augmented, mixed and virtual reality applications for tasks like warehouse picking and vehicle loading as the data from these tasks is well suited to the creation of digital twins in these environments (Dohrmann et al., n.d.; Gartner, 2023).

This sounds exciting, but it is no way close to what is needed. As one expert explained: “In a nutshell, the digitalization of logistics and the supply chain is like upgrading from an old bicycle to a sleek, high-performance sports car” (Burak, 2023). Implementing cutting-edge digital twin solutions is disruptive but very much needed in the sector.

Some examples of digital twins are already quite spectacular, and we are certainly seeing more efforts to build hub-format digital twins that go beyond the micro-application layer. A good example is the Port of Singapore, which has created a digital twin of its new shipping container megahub (this is discussed in more detail below, in the section on Maritime). And in 2019, it was reported that the Port of Rotterdam, in collaboration with IBM, had started developing a digital twin for its operations, to test various scenarios ‘online’. It is committed to becoming the first digital port by 2030, and the smartest port in the world (Boyles, 2019).

Yet, the adoption of digital twins is in its infancy. As explained above, digitisation is not alien to this sector, but it is largely fragmented, and the data-sharing and databases integration that are so relevant in this type of interdependent/interconnected environment, are still at a crawling stage. Many participants are reliant on offline processes that can be subject to errors and delays. In addition, the logistics sector’s inherent heterogeneity, fragmentation and vast geographic scale make it an almost hostile/adverse environment for a global ‘overarching’ adoption of digital twins. (Dohrmann et al., n.d.)

The ultimate digital twin dream would cover an entire network, including not just logistics assets but also ships, ports, railway lines, highways, streets and customer homes and workplaces. However, the idea of such an all-encompassing twin is largely an aspiration for the industry, and quite far-fetched for now.

The selected case study presents a simulation model for air freight load planning. Optimising this process has a direct impact on load time, security and profitability, and the challenges can be defined as follows: aircraft configuration, body planning, palletisation and weight and balance. From a technical perspective, it is interesting to see the fusion of mathematical models with virtual reality in the case study. The case study also illustrates how a ‘micro’ digital twin can easily illustrate the complexity of the data required to model the baseline for performing optimisation tests.

7.2.1. Case study 3 – Closed-loop air cargo digital twin

Table 15 Case study 3 - digital twin for closed-loop air cargo planning

WHY: THE PROBLEM	
Overview	Currently, it is almost impossible to make an accurate estimate of exactly how many goods can be carried without excessive risk. Goals: enhance cargo loading operations through simulation and optimised loading plans, minimise rework in physical cargo stowage, and provide a feedback mechanism for actual loading situations.
Transport service/infrastructure element	Boeing 747-8 F with a total of 34 positions
Spatial area	Simulated cargo route: John F. Kennedy International Airport - Calgary International Airport
Scale	System simulation

Elements to consider for high-degree similarity	Various compartments of an aircraft, cargo size and contour, discharging destinations, weight, dangerous goods segregation and cargo urgency, centre of gravity (CG) of the aircraft, weather conditions and air pressure at different altitudes, International Air Transport Association (IATA) Unit Load Device (ULD) code, serial number, contour, pallet dimension, ULD weight, cargo revenues, and objective function weighting.
HOW: THE SOLUTION	
Overview	A digital twin model for air cargo loading operations with an integrated system comprising a developed MIP mathematical model and simulation system to optimise the air cargo loading plan, cloud storage for load plans, a VR system for visualising and validating the load plan, and sensor systems to provide feedback on deviations between actual and planned cargo. Five scenarios simulated, including one with dangerous goods.
What data was recorded? How was it done?	The initial input consists of the information of ULDs, weight and balance requirements and cargo destinations stored in data tables of cloud data fusion.
Software layer/AI/ML	The MIP model is developed with the use of the LINDO system. A Cave Automatic Virtual Environment (CAVE)-based system is developed, featuring a cube-like structure with four 3D projectors and screens, an audio and acoustic system, server, display system, two high performance workstations, frame and tracking systems, 3D modelling and VR software, and 12 sensors. A 3D model of a B747-8 F aircraft for cargo freight has been developed using Maya for modelling, rendering and texturing. The model is focused on cargo loading on the main deck; thus, the interior of the aircraft with loading trajectory, locks and lighting is included in the multimedia design.
Cloud/data storage	Yes / Not specified
How does it work?	The optimal load plan generated from the optimisation model transferred via the cloud storage to the virtual reality system, which has built-in air cargo terminal and aircraft 3D models. The load plan visualised in CAVE VR platform in advance allowing operators observe and audit any errors in allocation and dangerous goods (DG) segregation. Motion sensors provided for tracking the movements of operators to facilitate better visualisation and viewing perspective. Abnormal handling issues such oversize cargo captured, before physically loading an ULD to avoid any cargo damage. If there is any abnormal handling issue detected when the ULDs are physically stowed into the aircraft, the detection sensors in the aircraft alert the operators via mobile devices. The captured data transferred back to optimisation model and simulate a new load plan which will be transferred to VR system via the cloud. The simulated cargo load plan is compared to the load plan generated by the airline's system which is mainly providing a feasible plan rather than an optimal plan. The VR platform and sensor feedback loop allow for the validation and detection of ULD positions with reference to the discharge destinations and dangerous goods segregation, eliminating incorrect positions of ULD being loaded.
Scalability	Other aircraft types

Output	The simulated results show improvement in the centre of gravity and loading arrangement when compared to the actual plan. Decision support system in recommending optimal plans, replacing manual feasible load plans, shortens the loading time required as validation and rework can be carried out in advance with the use of a VR platform and sensor detection feedback.
Decarbonisation	The simulated results show improvement, particularly in minimising the CG deviations, and hence reducing fuel consumption.
Worth noting	It is crucial to include CG in the calculations of the simulation, not only for safety and regulatory purposes but also for profitability. The closer the actual measured CG to the required limit, the less aircraft fuel will be consumed, leading to cost savings.
Source	(Wong et al., 2021)

7.3. Aviation

Digital twins in aviation refer to a cutting-edge technology that involves creating a digital replica or simulation of an entire aircraft, specific components or even an entire airport infrastructure.

Aviation is characterised by its multiplicity of stakeholders, the long lifespans of its assets (nearly 30 years of continuous active service for aircrafts), and its high requirements regarding safety, security and documentation. The industry is technology-intensive and, by its nature, has reached a high level of digitisation adoption. Unsurprisingly, it is also one of the most data-intensive industries: "In the Airbus A380 manufacturing, Airbus and its contractor need to process information from 4 million components. Further to this, a single flight test of a Boeing 787 collected data from 200,000 multi-modal sensors" (Li et al., 2022).

Digital twinning can be applied to a spectrum of operations in aviation, from design, testing and manufacturing to anomaly detection, as well as fleet management. The implications of digital twin implementation are profound. For instance, it is possible to carry out real-time system assessments, diagnostics and prognostics more precisely than with traditional health management methods. Repairs could be executed instantly, and innovation could be faster and more economical.

Digital twinning has been successfully implemented by manufacturers of aviation components to aid their production. As referenced in Chapter 2 (2.1.), Rolls-Royce, which produces engines used in aviation, currently utilises digital twins to finetune its engines and simulate a variety of conditions, called the Intelligent Engine. The digital twin of an engine is a meticulous virtual copy of the physical one. The latter is equipped with sensors and satellite connectivity to collect data and continuously send to the digital twin for real-time monitoring. This operation makes it possible to determine types of on-ground maintenance, which, most importantly, leads to shorter aircraft downtime. It also allowed Rolls-Royce to develop a new business model called 'Power by the hour', where the airline engine manufacturer committed to offer replacement and maintenance of the entire range of engine accessories, for a fixed rate per flight hour basis. The digital twin enables engineers to test under various conditions – often extreme – many of which would not be feasible to run on a physical engine (*Power by the hour*, 2022).

Digital twin technology is also used to create digital models of physical airport environments (e.g., building infrastructure, runways). A good example of this is San Francisco Airport which started to implement digital tools to manage the infrastructure and asset of the airport long before the digital twin reached the surface of global attention. It embarked on this over 15 years ago, with visualisation of the airport to plan and manage renovation works, using GIS, and later augmented this with Building Information Modelling for design data. The airport's emergency services were also integrated with GIS to stay up to date and monitor various levels of the airport through the real-time 3D visualisation. It is a highly complex ecosystem of geo-data encompassing airfield and buildings and underground utilities (Bills, 2021).

However, digital twinning is still not a smooth journey for the aviation industry. The high density of sensors, intra-connectivity of multiple systems, complex system configurations and generation of massive amounts of heterogeneous data pose significant challenges for operational massive data management. As stated above, the Airbus 380 consists of 4 million components; therefore, creating a bijective relationship between a physical aircraft and its digital twin faces significant technical obstacles. The large number of component subsets and different pieces of software results in significant interoperability issues (Sharma et al., 2022). Unfortunately, the simplification of processes, data sources is not really an option. The quality and accuracy of data streamed from sensors and connected devices used in aircraft components design is critical and cannot be compromised under any circumstances. Reduction of data streams is out of the question since only multiple data points and various sensors/devices safeguard data reliability (Li et al., 2022).

An interesting observation was made by Laukotka and Krause (2023), that while much of the required data is available in some form, generally there is a lack of a digitally usable dataset for the specific aircraft and a virtual representation of the physical asset is missing.

The selected case study, below, on cabin retrofitting is interesting in terms of data modelling. An attempt is made to integrate various documentation and information sources required in the process. As the authors explain, at the time of retrofit planning (every five to seven years) the aircraft is still in operation and still flying around the world, so a simple recording of the current state is often not feasible. Instead, the engineers plough through a pile of documents and often only know from experience where to look next.

The case study creates a digital-twin-inspired data modelling method to make the cabin retrofit process digitally feasible by improving access to digital data – through diverse classification and documentation within a system. It is an abstract case study based on realistic information from industrial project partners. By defining general information about aviation and aircraft, it is possible to create structured, digitised documentation that provides a basis for concrete implementations and, at the same time, improves the reusability of the information. The goal is not to have a holistic twin of every aircraft at once, but to organise the information used in each retrofit in a way that makes the job less difficult over time (Laukotka & Krause, 2023).

7.3.1. Case study 4 – Cabin retrofit modelling

Table 16 Case study 4 - digital twin for cabin retrofit

WHY: THE PROBLEM	
Overview	Digitisation of the planning and execution of the cabin retrofit. The study tries to answer: how can available meta-information regarding aviation and its retrofit be digitally defined and documented so that its usage eases the access to required but fragmented information during the planning and execution of aviation retrofit?
Transport service/infrastructure element	Aircraft
Spatial area	Airbus 320
Scale	PoC – data modelling for digital twin

Elements to consider for high-degree similarity	ATA spec: elements related to cabin, such as fuselage, air conditioning, oxygen, crew accommodations, passenger accommodations Generic information: applicable to all aircrafts of the same type (length, locations of doors) Semi specific: applicable to the same fleet (seat layout), Manufacture serial number: applicable to an individual aircraft (structural reinforcement)
HOW: THE SOLUTION	
Overview	Structured digitised documentation on generic aircraft information, integrated with specific aircraft data.
What data was recorded? **How was it done?**	The generic information can be collected from respective documents such as the Airbus A320 Family Maintenance Manual Airbus A320 Aircraft Characteristics Airport and Maintenance Planning, Cabin Configuration Guide, Ground Operations Manual , or a range of training manuals /original documents from partners while adhering to the intellectual property of the stakeholders. The data acquisition focuses on the actual acquisition of the previously defined information either in the form of collecting already available information from different sources or by creating new (digital) information by accessing the actual airframe and, e.g., performing measurements or visual inspections sources of the acquisition is aggregated into a dataset that can be handed to the modelling. Additionally, occurring references and dependencies as well as meta-information such as the sources, reliability, specificity, and also referable IDs are reviewed or added.
Software layer/AI/ML	The relations and meta-information are modelled using models similar to the system modelling language SysML.
Cloud/data storage	Classical data storage solutions such as PLM systems or file servers
How does it work?	Structured digitalised documentation is created by first defining generic information about aviation and aircraft, thus providing a basis for specific implementations while also improving the reusability of information. Subsequently, information specific to a single aircraft is added to the system model. The modelling is extended by a bridge from the created system models to a graph database. This allows for easy integration into user interfaces and furthermore enables usage of data science algorithms later on. The modelling approach is embedded into an overarching procedure, based on CRISP-DM, which also includes the definition of the retrofit as well as the phase of data acquisition.
Scalability	The model does not create digital twins of aircraft, the combination of generic and specific information allows for easier handling of the individual information of specific aircraft while also improving the overall data reusability. The approach enables the implementation of digital twins of specific aircraft focusing on the information needed for the retrofit. Because of the iterative approach and improved reusability of generic information, this becomes possible even for third-party stakeholders (which retrofit companies usually are).
Output	The methodology presented in the paper was implemented as a proof of concept.

	The user interface shows a generic overview in the form of an A320's base airframe, including referenced frames. The user can enter a type of aircraft, define a fleet or use a given manufacturer serial number to possibly preselect a respective dataset. Based on a selected area of interest, a more detailed view is given together with a first list of referenced and relevant documents. The levels of specificity are listed as well as filenames and the possibility to access the files if linked respectively.
Decarbonisation	Savings by reducing the amount for rework required for the retrofit.
Source	(Laukotka & Krause, 2023)

7.4. Rail

Railways are seen as the way to move forward in decarbonisation of transport. Efforts are increasing to shift more passengers and cargo on to the railways in order to reduce road traffic and meet the emissions reduction targets (for example, EU flagship programme Rail4Earth or Shift2Rail). In a way, these efforts help the railway return to the glory it enjoyed in the 19th century, when it was at the forefront of the Industrial Revolution. However, this change requires huge investments in network modernisation. Digital twins have the potential to facilitate this large-scale transformation.

The digitisation of railways began a few decades ago and today regulates many services such as online tickets, payments and reservations. It is by no means complete, however. The goal remains to fully digitalise rail operations, which would mean that all points of the infrastructure were fully connected: from signals, switches, wagons and bridges to the entire railway network. The digitisation of rail requires substantial financial investment in upgrading the rail infrastructure, but also a change of mindset and investment in watertight cybersecurity systems (Jung et al., 2022).

It is important to emphasise here that these aspirations should not be isolated and limited to a national network only (although a nationwide digital twin for railways would be already a tremendous achievement), but should have an international character. The international harmonisation of railway networks, which is not yet as advanced as in maritime and air transport, has a strong economic incentive. It is crucial to facilitate international freight transport and reduce the costs of cross-border transit. An example of harmonisation is the European Train Control System (ETCS) – a key enabler of digitalisation in Europe. ETCS and automatic train operation (ATO) are the essential pillars of the cross-border digitalisation of the rail sector (Jung et al., 2022). (It is worth noting, by the way, that ATO systems were piloted in the UK in 2018 by Thameslink (London) when it ran the first 'driverless' train (GoA Level 3 and 4, with the driver present in the cabin in emergency situations).

Coming back to digital twinning for rail, the opportunities that the new technologies offer are enormous. Twinning has the potential to transform rail infrastructure management by optimising the entire asset lifecycle: planning, maintenance and repair schedules. It can reduce inspection costs and time and allows engineers to simulate the impact of different scenarios on performance. A study by Sresakoolchai & Kaewunruen (2023) on identifying component defects shows that that using reinforcement learning integrated with digital twin can reduce maintenance activities by 21% and reduce the occurrence of defects by 68% (Sresakoolchai & Kaewunruen, 2023).

An interesting example of digital twinning in practice is the pilot between Spinview, an advanced digital twin start-up, and Transport for London (TfL) to test the technology on London Underground's Piccadilly line. The project includes monitoring of tracks and tunnels and is intended to provide data on noise and heat levels as well as CO2 emissions. As reported, Spinview will provide TfL with the digital model, data and tools to enable the organisation to manage the Deep Tube environment in a way that is smarter, safer and more efficient (Spinview, 2022).

Another UK-based example is the rail equipment company Alstom, which has built a digital twin to simplify the management of its train maintenance operations on the West Coast Main Line. One of Britain's busiest inter-city rail routes, the line connects London to Glasgow and Edinburgh via major cities in the English Midlands and Northwest. Ensuring maximum availability of the fleet of 56 Pendolino trains is a continuous challenge. Alstom's digital twin includes details of every train in the fleet, along with their operating timetables and maintenance regimes. It also models the available capacity at each of Alstom's five maintenance depots. Because the system is connected to live information on train locations and planned movements, it can continually adapt maintenance plans to accommodate urgent repairs. Maintenance planners also use the system for 'what if' analyses to explore the impacts of changes to maintenance strategies and train timetables (Dohrmann et al., n.d.).

Another interesting example is an Edinburgh-based startup, Machines with Vision, which is developing a unique map of rail track features, to position infrastructure monitoring data, with 30mm accuracy. Its solution links remote condition monitoring data and millimetre-accurate location data to create a centralised map of track features for the complete rail network.

When it comes to challenges, the sector has strong significant overlaps with others. Just as with the sectors presented in previous sections, the full-scale deployment of a digital twin, even if applied in the first instance to the most critical components, requires significant investment in the digital twin infrastructure, both physical and digital. This is not possible for the railways without first modernising the physical network and achieving an overall standardised infrastructure. Another challenge is the sheer volume of data and its heterogeneity, coupled with its dynamic, real-time nature, which can be overwhelming for the system designers and its users. It then needs to be processed and visualised in a way that is understandable to operators and managers.

The two selected case studies showcase the utilisation of various technologies towards a digital twin: sensors for remote monitoring of rail switches (an extremely critical component), and deep learning to foster the analytical power of the digital twin in anomaly detection on rail tracks.

7.4.1. Case study 5 – Railway turnouts with monitoring of weather conditions

Table 17 Case study 5 - digital twin railway turnouts

WHY: THE PROBLEM	
Overview	Remote condition monitoring of the railway turnout (switch) system, including. weather sensing devices, in order to prevent track buckling. Proof of concept stage.
Transport service/infrastructure element	Rail section ~300 mm long, type S49 (49E1) [Graphic:https://rails.arcelormittal.com/types-rails/transport-rails/european-standards/rail-s49-49e1]
Spatial area	A rail thermometer with wireless logger UbiBot WS1 WIFI was located outside the structure gauge (infrastructure gauge), parallel to the rail tracks of the monitored turnout. Timeframe: 21 January 2020 to 29 May 2020, in Poland
Scale	5002 data points / Observations were made inside the rail head in hourly cycles.
Elements to consider for high-degree similarity	Geometrical position, linear and angular values of the main points of the turnout. The state of the parameters and indicators at the characteristic points of the turnout. Current weather conditions: temperature inside the rail head (crown of the rail), humidity, ambient temperature, ambient light.

	Second difference rail temperatures indicator in railway turnouts.
HOW: THE SOLUTION	
Overview	A novel solution for monitoring the status of temperature and other atmospheric conditions using sensors and S49 (49E1)-type rail. The developed solution represents the measurement of temperature inside the rail head, humidity, ambient temperature and ambient light. A method for measuring the temperature inside the rail head S49 (49E1) type rail using a UbiBot WS1 WIFI wireless temperature, humidity and illumination logger equipped with a DS18B20 external temperature sensor integrated into an S49 (49E1)-type rail.
What data was recorded? How was it done?	A UbiBot WS1 wireless data logger with sensors was used to acquire data on ambient temperature values, temperature values inside the rail head, humidity and ambient light.
Software layer/AI/ML	N/a
Cloud/data storage	N/a
How does it work?	Synchronisation of the performed observations with the UbiBot IoT Platform is performed wirelessly in real time. Personalised configuration of the device is possible using the UbiBot App, which allows setting the minimum cycle of observation execution and notifications that inform the user in real time if the acceptable deviation range is exceeded. Additionally, the UbiBot WS1 works with IFTTT (If This Then That) to create connections with other smart devices, fitting into the fundamental approach of using digital twins in railroad turnouts with innovative weather monitoring. It also provides data export in CSV (Excel) and PDF format for applications such as Continuous Welded Rail condition monitoring. An external DS18B20 temperature sensor was placed inside the crown of the rail type S49 (49E1). A fixed measurement point was provided throughout the data collection period. A UbiBot WS1 WIFI device with built-in memory provides for data storage in case of temporary loss of wireless connectivity to the UbiBot IoT Platform (e.g., Internet connection failure). This ensures continuity of data history. Additionally, the user can remotely check the current battery status or connect a wired power supply to the device via the built-in micro-USB port. Access to measurement data from anywhere in the world provides additional control of the device's operation.
Scalability	N/a
Output	The research confirmed that the proposed solution provides the possibility of locating it in various critical points of the railway infrastructure. It also represents a significant addition to the fundamental approach of using digital twins in railway turnouts. Acceptance was also made of the use of the TgCWRII, the indicator of the second temperature difference in the monitoring of railway turnouts. The innovative solution is a complementary element to the fundamental approach of using digital twins in railway turnouts.
Decarbonisation	N/a
Worth noting	The observations indicated that rail steel is very sensitive to changes in atmospheric conditions (thermal stress)
Source	(Kampczyk & Dybeł, 2021)

7.4.2. Case study 6 - Infrastructure maintenance improvement using deep reinforcement learning integrated and digital twin

Table 18 Case study 6 - digital twin infrastructure maintenance

WHY: THE PROBLEM	
Overview	The railway system consists of many components and each component affects the others in different ways. Railway maintenance is a complicated and difficult task and prone to errors and ineffective resource allocation, such as over-maintenance of good-quality tracks. Machine learning is used for railway maintenance for different purposes such as defect prediction or track circuit maintenance. The accuracy of the prediction can be high as 80% which demonstrates the potential of machine learning. However, problems in the railway industry are complicated and complex. Deep learning seems to be able to achieve better performance than traditional machine learning because it can better caption the non-linear characteristics of the rail industry. Objective: develop a reinforcement learning model integrated with digital twins to improve the efficiency of railway infrastructure maintenance based on track geometry parameters and track component defects.
Transport service/Infrastructure element	Rail track
Spatial area	Track 30 km
Scale	Data 2016-2019 (over 300K samples to train the agent)
Elements to consider for high-degree similarity	Track geometry parameters Defect types Maintenance activities
HOW: THE SOLUTION	
Overview	Deep reinforcement learning integrated with a digital twin based on track geometry and component defects.
What data was recorded? How was it done?	Data collection is done by obtaining required data from track geometry measurements, defect inspection reports and maintenance records. Data used in the study was obtained from a 30-km railway section during 2016–2019 from MRS Logística S.A. There are more than 300k sections that can be used to input to the reinforcement learning model. Seven track geometry parameters. 71 different types of track component defects (grouped in five categories based on track components: ballast, fastener, rail, sleeper, and switch and crossing). Seven maintenance activities consisting of tamping, rail grinding, ballast cleaning, sleeper replacement, rail replacement, fastening components replacement, and ballast unloading.
Software layer/AI/ML	The reinforcement learning model is developed based on Python.. The reinforcement learning technique used in the study is Advantage Actor-critic (A2C).
Cloud/data storage	Yes, as a backup system. Not defined.
How does it work?	The digital twin model is developed using Autodesk Civil3D with built-in add-on Dynamo to achieve data management. The states and actions for the reinforcement learning model are stored in the digital twin model via the property set definitions

	After the reinforcement learning model is trained and needs to be used for the real-world application, results from the application can also be saved to the digital twin model. The reinforcement learning model will use the data extracted from the digital twin model to decide on the proper maintenance activities to perform in the following maintenance period. Deep reinforced learning: The agent is trained to take action by performing maintenance activities. There are 128 possible combinations of maintenance activities that the agent can choose to take action on. Each action results in the improvement of track geometry parameters and probabilities of track component defect occurrence. There are 12 states in the environment, which are seven track geometry parameters and five track component defect occurrences. The agent has to take action by choosing which maintenance activities it will perform. After taking action, the environment will react by generating a set of new states considering the proper values of each state based on the field data. This process will repeat until the end of the training. In this case, the number of states is set to 100. From this condition, the environment is developed based on the condition of this study to make sure that it will be suitable for real-world application. Rewards are defined in two categories which are rewards in terms of maintenance costs and penalties when there are defects. When the training is done, performance will be evaluated by comparing the number of performed maintenance activities and the number of defects. Two scenarios will be compared which are the data based on the field data and results from the reinforcement learning model.
Scalability	The proposed system can be classified as BIM maturity level 2 because it can support the collaboration between parties such as railway operators and maintenance operators. With good preparation, it can reach the goal of BIM maturity level 3 because every party can access the digital twin model to add information and apply information from the digital twin model completely. Level 5 can be achieved when different parties who can share the same digital twin model can perform the maintenance and store the data in the digital twin model.
Output	States and actions defined in the digital twin model and accessible for the user. The number of both maintenance activities and defects significantly decreased. In the case of maintenance activities, the number decreases from 963,000 to 763,000 (a drop of 20.76%). In the case of defects, the number decreases from 520,000 to 164,000 (a drop of 68.42%). The number of defects significantly decreases despite a 20% decrease in the number of maintenance activities.
Decarbonisation	20% reduction of maintenance activities leads to a reduction of the workload resulting from the maintenance activities and increased use of public transport.
Worth noting	All data can be stored in a single model and data can be used to make decisions during different stages of the project. The digital twin model also improves collaboration because the digital twin model can be shared with the relevant parties and responsible persons.

	The contributions of the study are it can be used as a guideline for railway operators to improve railway maintenance efficiency and it also has the potential to provide predictive maintenance plans which can reduce the number of defects, maintenance costs and possession time for railway maintenance.
Source	(Sresakoolchai & Kaewunruen, 2023)

7.5. Energy networks

It is impossible to talk about decarbonising transport without considering the energy sector. At its core, decarbonisation is about using 'less' fuel and energy and replacing traditional crude oil energy sources with renewables and new clean energy.

The current research suggests that the energy sector might be one of the most progressive when it comes to the adoption of digital technologies. A good example is the concept of the smart grid, introduced many years ago, which is the digital version of the electricity network that uses digital and sensing technologies to monitor and manage the transport of electricity from all generation sources to meet varying electricity demands. In that sense, it can be seen as a digital twin.

The smart grid capability is crucial for the sector given the current and future shift to hybrid energy sources and renewables, to make it resilient against fluctuations in both supply and demand. Digitisation enables high-precision projections of energy consumption on various scale such as on a daily, weekly or monthly basis.

As in other domains, digital twinning offers plenty of advantages such as testing certain scenarios – e.g., weather extremes – that would be impossible to perform on the physical infrastructure. This already represents a financial win for providers. Digital twins in the wind energy sector enable the design, monitoring and prediction of wind turbine performance. The energy sector at large has been using digital twins for quite some time, across the whole life cycle of physical assets from planning to operation and maintenance. Digital twins are a powerful tool to monitor and reduce carbon emissions by design to reach environmental and decarbonisation targets.

One of the valuable uses for digital twins, and at the same time an existing gap, is 'grid balancing'. With the decarbonisation agenda driving the electrification of transport (e.g., electric vehicles), the ageing infrastructure is unable to cope with the high levels of surge demand. Digital twins can facilitate balancing activities – often through switching on stored energy production – or incentives to charge at times of lower demand.

It is worth pointing out here that the standards to streamline the interoperations on the smart grid level are already in place, for example IEC 61850 and IEC 61970. Focusing on the machine-level semantics to enable information exchange, they are the foundation standards for power system management of the smart grid (e.g., SSEN Powertrack). The standards for digital twins are yet to come and the challenge is that they should accommodate sector-specific conditions while simultaneously remaining cross-sectoral applicable. The existing semantic interoperability in the energy sector is a very good base to build upon. Experts explain that the adoption of the digital tools for the grid management accelerated during the pandemic and the sector benefits from them at the moment, but it is not yet fully saturated yet (Bischofberger, 2022).

Diverse projects have been launched to pilot the adoption of digital twinning in the energy sector. An interesting one is TwinERGY, part of Horizon Europe, with the city of Bristol partnering. The project as a whole targets citizen awareness on consumption patterns and aims to foster more sustainable energy behaviours, and the Bristol Pilot explores how to improve energy efficiency and sustainable attitudes within communities. The pilot focuses on an active role for the citizen in the energy market, and involves a number of phases, selecting 12 representative households and working with people to co-design the deployment of monitoring and actuation capabilities.

Finnish electricity transmission system operator Fingrid worked with IBM, Siemens and other partners to build a digital twin of Finland's power network. The Electricity Verkko Information System, or ELVIS, combines eight different systems into a single application, providing Fingrid with a consistent, comprehensive, and continuously updated model of its network. The digital twin is used in day-to-day grid operations, helping staff to manage power flows and protection settings to meet demand without overloading transformers or transmission lines. It also supports design and planning activities, allowing the operator to simulate the likely impact of changes to grid configuration or investment in upgraded assets (Dohrmann et al., n.d.).

Royal Dutch Shell launched a project to develop a digital twin of an existing offshore production platform. In the Joint Industry Project, the organisation is working with simulation company Akselos and technical R&D consultancy LIC Engineering to implement new approaches to managing the structural integrity of offshore assets. The pilot project involved developing a structural model of the platform that will use data from sensors to monitor its health and predict its future state (Dohrmann et al., n.d.).

The Catapult for Energy Systems was commissioned by the UK's Department for Business, Energy and Industrial Strategy (BEIS) to develop a digital twin demonstrator for energy systems. Over 12 months, the project was tasked with developing two proof of concept demonstrators: a visual demonstrator developed in a collaboration between the Energy Systems Catapult, the Alan Turing Institute and CityScape Digital, and a technical demonstrator developed using some of the Catapult's core modelling capabilities for technical users. "The demonstrators show illustrative values for metrics related to the UK's decarbonisation activities, representing the effects of policies as changes to uptake and usage of energy-related technology types, at both a household and a national level, while also giving the user the ability to 'travel' backwards and forwards in time, to see changes in the energy system play out in front of their eyes" (Catapult, 2022).

The selected case study shows how digital twin simulations help power plant operators to gain a better understanding of the techno-economic impact of different operation conditions. The presented twin is a part of a Power Plant Smart Management (PPSM) platform being developed by China Energy's National Institute of Clean-and-Low-Carbon Energy. The core of the PPSM platform is its customised 'digital-twin' numerical models of the existing coal-fired power generation units. As the authors explain, digital twins can be employed to simulate and analyse each unit's actual operating performance in comparison to its optimal performance at varying operating conditions, to investigate the root causes of the performance deviations and to evaluate the cost-effectiveness of optimisation solutions (Xu et al., 2019).

7.5.1. Case study 7 – Coal power plant performance optimisation

Table 19 Case study 7 - digital twin coal power plant performance optimisation

WHY: THE PROBLEM	
Overview	In order to meet the power grid's demand to accommodate the increasing intermittent power supplies from renewables such as wind and solar power, many baseload coal-fired power generation units are required to operate in a load-following mode. This not only causes undesirable thermal stresses to the plants' pressure parts and turbomachinery, but also results in low thermal

	efficiencies and low-capacity factors that impair the economics of those power plants. The best way for those coal-fired power plants to stay competitive or to become more profitable is to improve their operating efficiencies to reduce the plant operating costs, of which 60-70% generally comes from fuel. Not all operators are aware that their units were originally designed and optimised for baseload operations and that frequent irregular load changes cause undesirable thermal stresses to the plants' pressure parts and turbomachinery, resulting in higher maintenance costs.
Transport service/infrastructure element	320-MWe power plant, a subcritical coal-fired thermal power plant.
Spatial area	China
Scale	Simulation / The operating data reported in the paper corresponds to 'representative' conditions during a period of steady-state operation near full load in the summer and winter of 2018.
Elements to consider for high-degree similarity	OEM plant design components and plant performance parameters – highly granular.
HOW: THE SOLUTION	
Overview	Power Plant Smart Management (PPSM) platform. A digital twin is a comprehensive physics-based numerical model of a power plant unit that can simulate the thermodynamic performance and calculate the heat and mass balance of the plant's overall system, subsystems and major plant components, respectively, for any given operating conditions.
What data was recorded? How was it done?	Data on plant operations and economics were provided by the plant operator.
AI/ML layer / software	The digital twin developed using the Thermoflow^{TM} software suite included models of the boiler island, steam turbine island and emission control equipment.
Cloud/data storage	N/a
How does it work?	The digital twin was configured and sized using the unit's OEM design specification data, which represents the unit's OEM design performance at 320-MWe base load. The digital twin was calibrated using the plant unit's recent operating performance data extracted from the distributed control system, which represents the actual performance of the thermal power plant unit. The calibrated digital model was validated by simulating the performances of various part-load operating cases that were well in line with the actual performances. The digital twin was employed to investigate various optimisation solutions within the boiler island to reduce the air-heater exit-flue-gas temperature without modification of the existing air heaters.
Scalability	The modelling analysis showed that this optimisation solution can be flexibly operated either to maximise electric output during peak time or to maximise fuel-cost savings during off-peak times for the best economic gain, based on the plant operator's preference.
Output	An optimisation solution was identified to reduce the boiler exit-flue-gas temperature by up to 25°C from its current level, leading to an improvement in the plant unit's heat rate by ~86 kJ/kWh, or equivalent to an ~2.6-g(sce)/kWh reduction of electricity coal consumption.

	A second optimisation solution was identified within the steam turbine island, which optimises the utilisation of the heat of the turbine bleed steam going to the deaerator. This solution has the potential to increase the plant heat rate by up to 15 kJ/kWh, or equivalent to a 0.5-g(sce)/kWh reduction in coal consumption.
Decarbonisation	The combination of the two optimisation solutions can potentially reduce the baseline electricity coal consumption from its current level by up to 3.5 g(sce)/kWh, or equivalent to an income increase of 875-1075 RMB/hour for the same fuel consumption of its current 320-MWe full load, based on the coal (sce) price of 600 RMB/tonne and electricity price of 0.372 RMB/kWh.
Worth noting	One factor significantly impairing the unit's operating thermal efficiency was the excessively high boiler exit (i.e., air-heater exit) flue-gas temperatures. The actual operating temperatures reached an average of 147°C and as high as 160°C at some points; this was much higher than the 134°C of the design case. The root cause of this effect was identified by the digital twin modelling analysis. It was revealed that a large fraction (up to nearly 50%) of the cold primary air stream into the air heaters was bypassed and used as tempering air to control the mills' outlet temperatures; this resulted in reduced heat transfer to the primary air stream from the flue-gas stream. This situation was more a hardware-design issue rather than an operating problem.
Source	(Xu et al., 2019)

7.6. Maritime

In the globalised world, where production capacities are being relocated from Europe to Asian markets, the maritime sector is the backbone of international logistics. Not surprisingly, it is heavily influenced by current global trends such as rising delivery costs and political pressure for decarbonisation. At the moment, global shipping generates 3% of worldwide greenhouse gases. (King, 2022). In that regard, digital twins could be an important support for shipbuilding and shipping companies in overcoming the challenges facing them (Giering & Dyck, 2021).

Decarbonising shipping can be divided into three main categories: optimising operations, optimising design and equipment, and low-carbon fuel alternatives. Digital twins based on measured system data are often proposed as a technical tool for shipping decarbonisation, at least in the context of energy savings and maintenance of good operational efficiency. A digital twin of a ship can be created using measured data from the operating vessel. Hinz et al. suggest to focus on optimising the ship from the early-concept design phase in order to create the greatest possible impact on the overall performance of the ship. This is also the time to ensure that the necessary capacity for future sustainable fuels is available on board the vessel (Hinz et al., 2023; King, 2022).

Digital transformation in the sector is driven by the desire to reduce costs and increase business effectiveness, as well as by increasing regulation in the industry and the large amount of data now available. At the same time, the sector faces various hurdles when introducing new technologies, such as high implementation costs, low-quality offshore connections, ageing decision-makers, a lack of investment initiatives, and a low level of modern digital technology penetration in the supply chain (Giering & Dyck, 2021).

As reported, the digital twin technology platform has not yet achieved the expected acceptance and wider implementation in the maritime industry. Most discussions about the application of digital twins have focussed on what can be learned from big data in ship operations, and to a lesser extent on how such new technology can help improve the upstream ship concept and basic design activities as well as detailed engineering (Garcia Agis et al., 2022).

Lee et al. (2022) provide some fascinating insights into the obstacles to adopting digital twins for real-time vessel operations. The first obstacle is the technical difficulty in predicting the marine environment, particularly in predicting wave development in the locations where a ship will pass in the near future. Current wave forecasting technology is mainly based on statistical analysis and relatively long-term forecasts, e.g., in the order of days or weeks, which are mainly predicted by weather centres. The second hurdle is that all analysis and predictions must be done in real time. In other words, the prediction of movement reactions and manoeuvrability must occur immediately and without any time delay, which might be difficult in the middle of an ocean. Furthermore, if the vessel operator decides to change operating conditions such as speed and course, the resulting performance must be predictable in a very short period of time (Lee et al., 2022).

Real-time data streaming and analysis from a vessel located in the middle of an ocean indicates clear connectivity limitations, although this state of affairs is improving as satellite 5G takes off, through the work of companies such as Starlink and Amazon Kuiper. In addition, edge computing capabilities enable certain twinning tasks to be performed with few or no delays.

The connectivity conditions are obviously different onshore in ports, with numerous ports worldwide adopting automation and twinning to boost productivity and modernise their operations. At this point, smart ports become a more important paradigm for handling increasing cargo volumes and increasing operational efficiency. In fact, as ports become more congested and cargo volumes increase, the need for accurate navigation through seaports becomes more pronounced to avoid collisions and the resulting consequences (Yigit et al., 2023).

A good example is the Port of Singapore, where digitalisation is the result of a long-term R&D programme fostering adoption of AI and digital twin technologies for maritime sustainability and decarbonisation, and cybersecurity. The Singapore Port Authority is working with a consortium of partners, including the National University of Singapore, to develop a digital twin of the container shipping mega-hub. In 2018, the National University of Singapore (NUS) and the Singapore Maritime Institute (SMI) established the Center of Excellence in Modeling and Simulation for Next Generation Port (C4NGP), worth SGD$18 million (approximately US$13.21 million). In 2022, the SMI awarded second-phase funding of SGD$10 million to promote the adoption of digital twins locally and internationally in the maritime industry. Various R&D projects to be developed include Tuas Port's digital twin, advanced port operation planning systems, performance analysis of future automation systems, and a digital twin for haulier services in Singapore. As reported, the digital twin approach has already delivered benefits during the design phase of the Singapore project, and the consortium is using its digital models to expedite the generation of potential layouts, and is using simulation systems to evaluate different operating scenarios. Eventually, the Port Authority hopes that the digital twin will help it to optimise management of the mega-hub facility. Through using simulation, for example, it will be able to choose the optimum berthing location for a vessel of any given size, taking into account the assets, space and personnel required for loading and unloading operations, and the need to share those resources between multiple vessels at any time (Admin, 2018; Dohrmann et al., n.d.; MPA, 2022).

In the UK, the Portsmouth International Port will receive a digital twin demonstrator as the result of a R&D project worth £1.5 million. The Shipping, Hydrogen & Port Ecosystems UK (SHAPE UK) project is part of the Clean Maritime Demonstration Competition, funded by the Department for Transport and delivered in partnership with Innovate UK. IOTICS, partnering in the project, will create a digital twin of Portsmouth International Port to demonstrate an achievable modular green hydrogen generation system within the port. It is committed to becoming the first carbon-neutral UK port by 2030, and the first zero-emission port by 2050. It is also worth noting that the port of Portsmouth is already using several digital twins to map air quality across its facilities, and AI to identify trends or events of poor air quality (Valerio, 2023).

Finally, UNESCO's Intergovernmental Oceanographic Commission was mandated to launched the 'Ocean Decade', a programme to foster research on oceans with the aim to promote science-based policy-making to protect the ocean ecosystem, and also to secure a balanced ocean-based economy. Part of the framework is a digital twin of the ocean (DITTO) to quantify benefits and environmental change and provide powerful visualisations.

The selected case study is a "mini" scale digital twin compared to the Port of Singapore. Nevertheless, it offers a good insight into the technical details of such a project. It also shows how a digital twin can improve the functioning of a port in terms of trajectory performance by approximating the desired shortest path. It represents a solution that can both reduce operating costs and minimise fuel consumption, contributing to decarbonisation.

7.6.1. Case study 8 – TwinPort Port of Leith

Table 20 Case study 8 - digital twin Port of Leith

WHY: THE PROBLEM	
Overview	Accurate ship navigation is critical in congested seaport areas to prevent delays, downtime and collisions that can cause significant damage to property and loss of life.
Transport service /infrastructure element	320m-long container
Spatial area	Port of Leith, Scotland
Scale	Ship manoeuvring — simulation model
Elements to consider for high-degree similarity	Static physical properties of the ship container: length, breadth, draft, block coefficient, longitudinal centre of gravity, vertical centre of gravity, metacentric height, propeller diameter. Physical and geographical properties of the port, real-time drone observations.
HOW: THE SOLUTION	
Overview	The TwinPort architecture combines digital twin technology and drone-assisted data collection to provide precise ship manoeuvring in the maritime sector. The study proposed a three-layered approach, which includes physical-to-virtual (P2V) and virtual-to-virtual (V2V) communications, to create a comprehensive digital twin architecture for smart seaports. The system finds the best location for the line-up procedure and calculates the quickest and most appropriate path by taking into account variables like open slots in the ports and the ship's features.
What data was recorded? How was it done?	The components of the primary drone-assisted data collection network include sensors, a drone, a control station, a base station, and a server. 1. The sensors discern the environment according to their unique properties and send data to the drone.

	2. The drone collects data while flying over the ships, then transmits it to the server. 3. The control station automatically designs the drone's flight path to optimise data collection. 4. The base station receives sensing data from the drone. 5. The server stores and sends the data obtained from the sensors to the connectivity layer.
Software layer/AI/ML	Eclipse Hono, Eclipse Ditto, and MANSIM tools - open source - used to build a comprehensive simulation. Google Maps for satellite imagery and geographical data.
Cloud/data storage	The data is stored on both the server physically and the service layer digitally.
How does it work?	The first layer, *Data Layer*, is comprised of seaport physical entities, such as IoT devices, which generate real-time data. This layer is the foundation of the digital twin architecture as it enables the collection and transmission of data to the subsequent layers. The second layer is *Twin Layer*, which gives digital replicas of the physical entities. The Twin Layer is responsible for modelling and simulating the physical seaport, enabling stakeholders to monitor and analyse seaport operations. *Service Layer*, the third layer, includes smart seaport applications, such as a recommendation engine and manoeuvre forecasting. This layer uses data that comes from the twins created in the Twin Layer to provide insights and predictions on seaport operations. 1. The required data is taken from the twin layer. 2. The modular mathematical model of the ship is built. 3. Empty slots in the seaport are checked, according to the ship's properties. 4. The best appropriate area is defined for the line-up process of the ship. 5. The shortest path, named the desired path, is determined. 6. Then the actual path is calculated. 7. The specifications are created according to the actual path for precise manoeuvrings such as heel angle, drift angle, speed, roll velocity, and more. 8. After that, these specifications are sent to the master mariner. 9. The best area of the ship is held until the decision. 10. If the master mariner accepts the recommended route, the reserved port area is signed as busy in the system. 11. On the other hand, if the master mariner does not accept the recommended route, the reserved port area is signed as empty in the system. 12. A specific time slot is defined for this decision process. If the system does not get a response from the related ship, the reserved port area is signed as empty.
Scalability	The architecture built in this study may be used in confined waters such as straits, channels, or rivers where there is a need for precise ship manoeuvring.
Output	Path (ship trajectory) visualisation. The proposed three-layered architecture for smart seaports' digital twins provides a comprehensive solution for monitoring, analysing, and optimising seaport performance. The solution provides practical insights into seaport processes and enhances seaport efficiency and sustainability.

Decarbonisation	The proposed architecture aligns with the Gemini Principle, especially considering the global net-zero directions and actions. The proposed 5G drone-assisted data collection system using digital twin for smart seaports saves up to US$135 per hour, US$3,240 per day, and US$1.18 million per year, while also reducing financial expenditure, protecting the environment by minimising fuel consumption, and reducing GHG emissions, resulting in significant environmental benefits. All these results reveal the effectiveness of the proposed model implemented on the seaport and ship.
Source	(Yigit et al., 2023)

7.7. Conclusion

This section has provided a comprehensive, insightful case-based overview of how digital twinning technology is transforming the transport sector and what challenges it encounters. The selected case studies show a broad spectrum of applications of digital twins and where advances are needed or emerging.

The insights gained show that all industries have similar aspirations and challenges. The goal is to build an all-encompassing digital twin that drives even greater efficiency, security and innovation through the use of real-time data, advanced analysis and simulation technologies. The challenges to this are clear, with foremost among them the growing complexity of the system. This can overstrain computing resources and require significant infrastructure investments. The vast and heterogenous stream of real-time data demands serious capacities to handle, process and analyse this data efficiently. Digital twins need to work with diverse systems, sensors, and devices, and ensuring seamless interoperability between different components can be difficult, especially when dealing with legacy systems that may not have been designed with interoperability in mind.

Developing and maintaining digital twins can also be costly, as we have demonstrated in Chapter 3 (3.3.1.). Businesses and organisations therefore need to carefully evaluate ROI to allocate resources. Although digital twins are praised for offering so many benefits, it is unlikely that major investments will be made in digital twin infrastructure in the absence of strong business case. Until we reach the capacity for large-scale digital twins, industries will test different model sizes and applications for the technology. Greater acceptance of this digital tool in the industries presented is almost a given, and we have yet to see to what extent this will take place.

8. WP7 Project "Petras IoT"

The PETRAS National Centre of Excellence is a consortium of 24 research institutions and the world's largest socio-technical research centre focused on the future implementation of IoT. It started in January 2019 and will run until June 2024. PETRAS exists to ensure that technological advances in the Internet of Things (IoT) are developed and applied in consumer and business contexts, safely and securely. This is done by considering social and technical issues relating to the cybersecurity of IoT devices, systems and networks.

PETRAS is developing research expertise that includes a specialist focus on artificial intelligence and machine learning for edge and IoT devices.

PETRAS projects involve collaboration with academia, industry and government to deliver research that spans the physical and behavioural sciences and considers the issues of privacy, ethics, trust, reliability, acceptability and security as they relate to IoT devices, systems and networks.

The sectors 'Transport and Mobility' and 'Infrastructure' within the PETRAS program contain cybersecurity, privacy and related aspects that are relevant to TransportDigital Twin (TDT) development. The projects are outlined in the next section, where key technologies related to TDTs are highlighted.

8.1. Completed Projects

8.1.1. P-CARS

Project Title

P-CARS - Privacy in Connected Autonomous Cars and Smart Transport Systems

Description

The objective of the P-CARS project is to analyse and propose effective solutions for preserving the privacy of users within the context of communications among autonomous and semi-autonomous cars and cloud computing infrastructures, i.e., vehicle-to-everything (V2X) communications. Early analysis of the most promising existing solutions based on pseudonyms, indicates significant shortcoming of such solutions for the particular application to connected autonomous functions in smart transport systems.

Key Technologies

User privacy; identity management; V2X communication technologies

Key Words

Privacy preservation; autonomous cars; V2X Communications

Relevance to Transport Digital Twins (TDTs)

Privacy and security for connected autonomous vehicles and their communication with cloud computing infrastructure.

8.1.2. RoadMaPP

Project Title

RoadMaPP - Smart Road & Street Maintenance, Pricing and Planning

Description

This project involved the development of three strands of work, led by teams from Lancaster and Imperial. The first strand involves identifying the trust issues involved in putting highways maintenance data into an Internet of Things (IoT) hub. A case study will be developed based around the M25 motorway utilising an existing relationship with InTouch Ltd and Connect Plus Services. The second strand of work will build upon an existing framework for dynamic pricing in combined electric vehicle parking and charging markets. The third strand will develop the algorithms and tools necessary

to clean, integrate and analyse the heterogeneous data coming from the large-scale sensor deployment of TfL as well as third parties. Key to enabling trust in the results of the analysis is to design and deploy efficient and scalable algorithms for tracking the provenance of massive amounts of real-time events/data.
Key Technologies
IoT; dynamic pricing frameworks; data integration and analysis; provenance tracking algorithms
Key Words
Highways maintenance data; EV parking and charging; sensor deployment; heterogeneous data; provenance tracking; data integration
Relevance to Transport Digital Twins (TDTs)
Trust issues and data integration challenges in the context of highways maintenance and EV charging; development of a trusted hub for shared maintenance information; efficient algorithms for data tracking; informed road planning and decision-making process
University
Lancaster and Imperial College London.

8.1.3. GEOSEC

Project Title
GEOSEC - Lightweight Security and Privacy for Geographic Personal Data and Location based Services
Description
The objective of the GEOSEC project is to analyse and model the security and privacy weaknesses of existing techniques for location, place and geography information delivery (e.g. personal data disclosure, Personally identifiable information (PII)) and enabling trust in location based services (e.g. by proximity). The project also aims to propose secure and privacy preserving solutions to enable geographic information about locations and places to be a trusted and integral part of the Internet of Things (IoT) information infrastructure. The project will state clearly the security/privacy enhancement of the geographic information and services that are needed to support better IoT systems in the future. This project will initially focus on a number of well-known use cases (themes) such as: 1) connected and autonomous vehicles (CAV) and intelligent transportation systems (ITS), 2) smart ambient public spaces, 3) IoT-enabled smart road and street planning, pricing and maintenance.
Key Technologies
Security and privacy; geographic information exchange; IoT infrastructure
Key Words
Security and privacy weaknesses; location-based services; personally identifiable information (PII); IoT-enabled smart road planning; lightweight and scalable security techniques
Relevance to Transport Digital Twins (TDTs)
Contribute to the safe and reliable operation of TDTs by addressing critical security and privacy concerns related to location-based services and IoT systems.

8.1.4. B-IoT

Project Title
B-IoT - Blockchain Technology for IoT in Intelligent Transportation Systems
Description
Huge benefits in transportation can be gained if Intelligent Transportation Systems such as automated vehicles are enabled to communicate between each other, and their surrounding infrastructure in ways that are simple, reliable, and widely acceptable for human operators. At the same time, it is imperative that the security and privacy of such communications are considered. This project will demonstrate the potential of distributed ledgers such as blockchain as a method of securing the integrity of such systems.
Key Technologies
Blockchain for IoT systems within the context of Intelligent Transportation Systems (ITS)

Key Words
ITS; distributed ledgers; blockchain technology; security and privacy; location verification
Relevance to Transport Digital Twins (TDTs)
Enhancing security and privacy in ITS. The use of blockchain for securing IoT comms can contribute to ensuring the integrity and security of data and comms within TDTs
University
Edinburgh & Imperial College London

8.1.5. DDIP-IoT

Project Title
DDIP-IoT - Designing Dynamic Insurance Policies using IoT
Description
This project explored how 'real-time' adjustable insurance policies can be designed and managed using Internet of Things (IoT) technology. Typical examples include bike/car renting, car sharing, and courier services where there is varying level of risk. The project will look into the mechanisms and models that insurers would need in order to implement 'real-time' adjustable insurance policies.
Key Technologies
IoT; real-time assessment of insurance policies
Key Words
Dynamic insurance; risk assessment
Relevance to Transport Digital Twins (TDTs)
By leveraging IoT data, insurers can dynamically adjust policies based on changing risk factors, enhancing the safety and efficiency of mobility services. This aligns with integrating real-time data into TDTs to optimise decision-making and risk management.

8.1.6. TMDA

Project Title
TMDA - Transport and Mobility Demonstrator Audit
Description
The importance for Transport and Mobility demonstrators to the UK has been recognised by UK Government, Industry and Academia. Many initiatives have been launched but ensuring maximum strategic benefit, especially to ensure security and resilience, requires further work. The aim of this project is to develop guidelines and policy recommendations for UK Government and industry.
Key Technologies
N/A
Key Words
Policy recommendations; strategic benefit
Relevance to Transport Digital Twins (TDTs)
Developing guidelines and policy recommendations for Transport and Mobility can contribute to TDT enablement.

8.2. Current Projects

8.2.1. DigiPort

Project Title
DigiPort - From Logistics 4.0 to Digital Ports: A study in transformability using DLTs
Description
The DigiPorts project takes the work and know-how from the PETRAS project Logistics 4.0 and investigates its implications on the efficiency and security of ports. The aim is to allow the work of PETRAS to inform a country-wide solution to smart ports directly.
Key Technologies

Distributed ledger and tag technologies; IoT Tags
Key Words
Smart ports; security; logistics
Relevance to Transport Digital Twins (TDTs)
In the context of smart ports, contribution to logistics through secure data transfer and goods tracking.
University
Imperial
Industry Partners
Modini, Openbrix

8.2.2. PRISTINE

Project Title
PRISTINE - Privacy-preserving Data Sharing and Trading Ecosystem for Distributed Wireless IoT Networks
Description
The PRISTINE project is establishing a sustainable data sharing and trading ecosystem for massive, low capability and wireless connected heterogeneous IoT devices in a privacy-preserving and secure manner. Smart contracts will be adopted in distributed ledger technology (DLT, or blockchain) to underpin access, quality control, trustworthy and high throughput transactions between data providers and consumers.
Key Technologies
Blockchain; data sharing; heterogeneous IoT devices
Key Words
Data sharing; privacy preservation; trustworthy transactions
Relevance to Transport Digital Twins (TDTs)
Enhance data security and access control of IoT devices. Addressing challenges related to device heterogeneity, economic and social aspects.
University
Glasgow
Industry Partners
Toshiba Research Europe; Medicalchain; Nakamoto & Turing Labs

8.2.3. UMIS

Project Title
UMIS - Increasing User trust in Mobility-as-a-Service IoT ecosystem
Description
The UMIS project investigates mechanisms for increasing user trust in Mobility-as-a-Service (MaaS) in an IoT ecosystem for the next-generation transportation-systems.
Key Technologies
MaaS; data governance; data protection
Key Words
User trust; MaaS; secure data sharing; privacy protection; data exchange; data protection
Relevance to Transport Digital Twins (TDTs)
Creation of a data governance framework that ensures secure and privacy-preserving data usage and sharing can contribute to building trust in the data used by TDTs. Establishing a foundation for reliable and ethically managed data in next-generation transportation systems.
University
Southampton
Industry Partners
Solent Transport; Immuta Ltd; KnowNow Information Ltd

8.2.4. CoSTCMoRS

Project Title

CoSTCMoRS - Cognitive and Socio-Technical Cybersecurity in Modern Railway Systems (CoSTCMoRS)

Description

The CoSTCMoRS project is developing a hybrid and adaptive approach to combining AI and a socio-technical model to identify and detect cyberattacks and create a holistic & fast response to cyber incidents to ensure the security, safety, and functionality of a modern railway system (MRS). The project focuses on the Signalling and Control System (SCS), on which an attack tree analysis will be given. The project also aims to provide a socio-technical security roadmap and IoT plan for business continuity to mitigate the potential impact of cyber incidents on MRSs, considering the operations, human-factors, organisational structures, regulation and policies.

Key Technologies

AI; Socio-technical model; IoT infrastructure; Cybersecurity; Automation

Key Words

Modern Railway System (MRS); Security response; Security automation; cybersecurity; resilience

Relevance to Transport Digital Twins (TDTs)

Using AI and socio-technical models to identify and detect cyberattacks, enhance the security of data used in railway systems. Creating a security roadmap can help ensure the resilience and continuity of rail services in the face of cyber threats.

University

De Montfort, UCL

Industry Partners

NSAR; Birmingham Centre for Railway Research & Education; East West Rail Co; COSTAIN; Vega Systems UK; CERBERUS Security Laboratories

8.2.5. AMLoE

Project Title

AMLoE - Adversarial Machine Learning on the Edge

Description

The AMLoE project investigates vulnerabilities of machine learning (ML) when deployed on the edge and aims to produce new means of testing and improving their robustness whilst not compromising significantly on accuracy and performance.

Key Technologies

ML; edge computing; adversarial attacks; robustness testing

Key Words

Edge deployment; ML vulnerability; ML robustness; data compression; data quality and accuracy

Relevance to Transport Digital Twins (TDTs)

Ensuring the robustness of ML models at the edge contributes to the trustworthiness and reliability of TDTs. Improving data quality and accuracy of data used in TDTs.

University

Imperial College London

Industry Partners

DSTL; Thales; DataSpartan

8.2.6. MAISE

Project Title

MAISE - Multi-Modal AI-based Security at the Edge

Description

The MAISE project investigates the resilience of Artificial Intelligence (AI) and Machine Learning (ML) models on IoT-scale devices.

Key Technologies
AI/ML; resilience; user authentication
Key Words
AI/ML models; IoT devices; Edge
Relevance to Transport Digital Twins (TDTs)
Ensuring security and resilience of AI models on edge devices contributes to the integrity of TDTs. By addressing adversarial threats, the safety and reliability of TDTs can be enhanced, by preventing unauthorised access, tampering.
University
Glasgow
Industry Partners
ST Microelectronics; SICSA

8.2.7. TOMSAC

Project Title
TOMSAC - Trade-off Management between Safety and Cybersecurity
Description
The TOMSAC project aims to propose novel and effective solutions for managing trade-offs between cybersecurity and safety in converging Cyber Physical (CPS) and Internet of Things (IoT) systems.
Key Technologies
Cyber-Physical Systems; Cybersecurity
Key Words
Safety-cybersecurity trade-offs and interdependence
Relevance to Transport Digital Twins (TDTs)
Novel methods for managing trade-offs between safety and cybersecurity for real-time data from IoT devices. Recommendation of relevant international standards and guidelines.
University
Coventry
Industry Partners
HORIBA MIRA Ltd

8.2.8. MAGIC

Project Title
MAGIC - Multi-Perspective Design of IoT Cybersecurity in Ground and Aerial Vehicles
Description
This project aims to achieve security and resilience for future vehicular systems. It tackles the limitations of current approaches to cybersecurity in the transport sector by introducing new modelling and verification techniques based on digital twins. The approach contains multiple design perspectives, each one encompassing a property of concern.
Key Technologies
Cybersecurity; modelling and verification; resilience; autonomous systems; AI
Key Words
Security and resilience; modelling & verification; autonomous vehicles
Relevance to Transport Digital Twins (TDTs)
Ensure the resilience and security of autonomous and cooperative systems by using digital twins, modelling and verification techniques. Contribute to the safety and reliability of TDTs by helping to prevent issues and vulnerabilities that might arise after deployment.
University
Glasgow
Industry Partners
NXP Semiconductors; Blue Bear Systems Research Ltd

8.2.9. AIKEMA

Project Title

AIKEMA - AI for Key Management and Mitigating Attacks (AIKEMA)

Description

AIKEMA addresses how machine learning approaches to automated security key management within the transport sector (e.g. autonomous vehicles) could help manage network load and intrusion detection. This helps to better understand and mitigate risk, particularly within 5G systems.

Key Technologies

ML; automated key management; intrusion detection

Key Words

autonomous vehicles; data security; key sharing techniques

Relevance to Transport Digital Twins (TDTs)

Automated key management can enhance data security and reduce human error, essential for maintaining the integrity of TDTs.

University

Surrey

Industry Partners

Telefonica

8.3. Summary of Key Research Areas

1. Privacy and Security
   Several projects develop concepts related to user privacy and data security in the context of connected autonomous vehicles, IoT networks, and transportation systems. (Projects: P-CARS, GEOSEC, B-IoT, DDIP-IoT, UMIS)

2. Data Integration and Trust
   Research in several projects is focused on data tracking, data integration and trust in the information shared among different components of transportation systems. (Projects: RoadMaPP, DigiPort, PRISTINE, CoSTCMoRS, MAGIC)

3. Blockchain Technology
   Blockchain technology is researched as a means to enhance the security and integrity of data and communications within intelligent transportation systems. Its application can contribute to secure data transfer and protection against cyber threats. (Project: B-IoT)

4. Dynamic Policies and Risk Management
   A project is investigating the dynamic adjustment of insurance policies and risk assessment using real-time data from IoT technology. (Project: DDIP-IoT)

5. Resilience and Safety
   Ensuring the resilience and safety of transportation systems is a common goal across various projects. AI, socio-technical models, and cybersecurity measures are applied to identify and mitigate cyberattacks, enhance data security, and support business continuity. (Projects: CoSTCMoRS, AMLoE, MAISE)

6. Data Governance
   Establishing data governance frameworks is vital to ensure secure and privacy-preserving data usage and sharing. This, in turn, contributes to building trust in the data used by transport

digital twins, fostering reliability and ethical data management in next-generation transportation systems. (Project: UMIS)

7. Robustness of Machine Learning
The robustness of machine learning models at the edge is a key focus to maintain the trustworthiness and reliability of transport digital twins. Improved data quality and accuracy are key for their successful deployment. (Projects: AMLoE)

8. Trade-offs between Safety and Cybersecurity
One project's aim is to propose effective solutions for maintaining the integrity of real-time data from IoT devices while ensuring its security. (Project: TOMSAC)

9. Multi-Perspective Design and Verification
Enhancing the security and resilience of autonomous and cooperative systems is a priority. Digital twins, modelling, and verification techniques are employed to prevent issues and vulnerabilities that may arise after deployment, contributing to the safety and reliability of transport digital twins. (Project: MAGIC)

10. AI and Machine Learning
Machine learning approaches are explored for automated key management to help manage network load and intrusion detection, crucial for maintaining data security within transportation systems, particularly autonomous vehicles and 5G systems. (Project: AIKEMA)

These key research areas and their corresponding projects contribute to the development and implementation of transport digital twins, enhancing the security, reliability, and sustainability of modern transportation systems.

9. WP8 Transport digital twin challenges and research opportunities

The main purpose of this report is to understand the current state of the art for developing and implementing transport digital twins and based on these results, identify open questions and technical and socio-economic challenges that lead to research opportunities for the coming years.

This section pulls together the findings from the previous sections on the “gaps” in the digital twin ecosystem that require further research and development to foster the adoption of digital twins in transport, and also in the wider ecosystem It provides actionable recommendations on what activities should be undertaken by research groups to strengthen the foundations for adopting digital twins in the industry. Our recommendations require multi-disciplinary research to cover a variety of facets of digital twins.

9.1. Digital Twin in socio-economic context

- Research how the risks of design, operation, and maintenance of digital twins by human can be mitigated, e.g., error checking, integration validation and automated insider threat assessment and detection.
- Address the challenge of how human behaviour affects the accuracy of digital twin analysis and how fast a digital twin can adapt to new socio-economic occurrences, new business models (on-demand delivery, MaaS).
- Explore how human behaviour can be captured in data models, e.g., in urban mobility digital twins, and develop models of human behaviour in transport. Analyse how Living Labs can support the technical research by providing more real-world context and sociological aspects. Research in e-commerce and retail can provide valuable insights.
- Explore how digital twin affects an organisation in terms of its culture, overall technology acceptance within an organisation, staff training, operational activities and internal policies and processes. Explore how change management can support the digital twin transformation in an organisation.
- Define KPIs to verify and validate the success and impact of digital twin implementation in transportation, including decarbonisation parameters. Research by Courraud et al. can serve as a good starting point for further exploration in this area.
- Develop a playbook on methods and approaches to help organisations define problems they could address with digital twins, and how they could develop a business case/ROI for digital twin implementation. Paradoxically, the long list of benefits from digital twins does not provide sufficient clarity on how challenges within an organisation could be addressed through digital twins.
- Define a KPI framework to measure flexibility, scalability, and accuracy of digital twin methods such as simulations, analytics and visualisations (e.g., how easily can a digital twin method adapt to a new use case, and how much modification does it require?). This can promote sustainability in digital twin development and measure reusability of methods and models in different applications with as little intervention and adjustments as possible.
- Research into the carbon footprint of the digital twin implementation (in terms of the life cycle of its complete infrastructure), provide methods to calculate it, and guidance on how to mitigate and minimise that impact.
- Contribute to the mapping of the skills required to train a new generation of professionals to understand the complexity of building secure digital twins connected to wider cyber-physical systems. This may result in the development of both college and university-level curriculums and CPD courses for upskilling the existing workforce. This is likely to require both an understanding of the operation of transport and energy systems and technologies including IoT and sensor systems, cloud computing, ML/AI, simulation/emulation and visualisation. This area may be a good candidate for a Centre for Doctoral Training.

- Explore methods to incentivise data sharing such as collaborative or regulatory mechanisms (a code of conduct, contracts, regulations, or licenses to operate a digital twin). Sharing information will be easier if all stakeholders involved benefit from the exchange by for example, better resource planning.
- Explore modelling techniques and infrastructure requirements to support the development of a multi-modal transport digital twin, e.g., freight. Research should focus on understanding interdependencies in the cyber-physical networks and include analysis of risks and opportunities from the inevitable/necessary integration of the energy network in the multi-modal digital twin.

9.2. Cybersecurity

- Undertake a detailed mapping of **standards and regulations** for digital twinning for decarbonisation of transport – this is required to understand areas of compliance for both cyber and physical aspects given the wide range of sectors, technologies and processes. Aspects of cyber physical security, resilience, privacy and trust are likely to be embedded in existing standards and regulations, however, this mapping will highlight opportunities to innovate and contribute to existing bodies undertaking activities in this space. For example, ISO/IEC's JTC 1/SC 41/Working Group 6 specifically focuses on digital twin standardisation, including related technologies of digital twins. The result of the mapping may be the need for the development of a specific standard and/or framework focussed on secure decarbonisation of transport systems.
- Research into **cyber-physical security and resilience** for networks of digital twins in which these systems of systems may exhibit different behaviours and present additional risks to the underlying enabling technologies.
- Specifically address the challenge of **assessing and preserving the veracity of data** exchanged between digital twins and also between twins and their associated physical counterparts, as a means to aid adoption and build trust in the use of digital twins. This may also need to look at the ingestion of data from questionable sources, e.g., third-party sensors. Aspects of the management of shared and open data exchange should be explored, along with techniques for preserving privacy.
- Explore the **management of security, resilience and privacy responsibility** across multi-domain cyber-physical systems involving evolving digital twins. Investigate if an automated process can be implemented to flag areas of joint responsibility and where responsibility is unclear.
- Research how unusual events, such as **emergencies**, may need to be addressed by trading-off aspects of security in order to enable a more rapid response in a digital twin network.
- Define a **secure modular digital twin architectural template** and network of twins template for the decarbonisation of transport which meet the existing requirements and is extensible to address future needs, including changes in the cyber physical threat landscape.
- Research how a **distributed active defence function** can be designed into digital twin networks which can adjust to rapidly evolving threats through techniques such as federated learning.

9.3. Physical Infrastructure

- Explore methodologies for ensuring the long-term integrity of digital twin systems and identify approaches for the design for digital resilience. This could adopt one of the fundamental principles of transport vehicular safety, that of redundancy. Given the potential future dependence on DTs, should architectures be considered that consist of a DT of a DT.
- Explore how digital twin systems can be designed to build resilience against rare and catastrophic events, such as the one that affected the UK Air Traffic control system in September 2023(see section 3.9).
- Investigate role of AI and ML and implementation methods to partly or fully address the sensor reliability issues (degradation, breakdown, connection and communication) in context of resilient design for digital twin, utilising capability of failure prediction and correction.

- Research into integrating and leveraging heterogeneous communication sources through digital twin technology for real-time decision-making. Explore how the integration and leveraging of heterogeneous communication sources through digital twin technology can enhance real-time decision-making, traffic management, and network efficiency in transportation systems
- Explore the digital twin system architecture allowing continuously emerging technical developments in the sensor technologies to be integrated periodically, as well as, allowing system scalability.
- Investigate the opportunities to expand the focus of digital twin development beyond traffic management, efficiency, and cost improvement and identify new business opportunities built on one or more components of the digital twin infrastructure. This could include logistics and supply chain; where digital twins can simulate various risk scenarios, such as natural disasters or supply chain disruptions, enabling companies to proactively plan for contingencies, secure supply chains, and minimize disruptions' financial impact.
- Research into what open, scalable, and amalgamated solutions can be developed to make data more accessible for the public good, reducing lock-in to proprietary systems

9.4. Digital infrastructure

- Investigate methods to enhance data quality and accuracy, addressing issues related to calibration, missing data points and sensor drift.
- Develop robust data security methods for transportation systems to ensure the confidentiality and integrity of sensitive data such as real-time location information, personal traveller data and details regarding the critical infrastructure.
- Research efficient data management frameworks for transport digital twins, optimising data handling and storage techniques such as compression and de-duplication.
- Develop advanced and efficient data processing techniques to handle and analyse large amounts of data in real-time.
- Develop standardised data formats and protocols for effective data integration and enhanced interoperability.
- Investigate methods to efficiently combine disparate, heterogeneous data sources in transport digital twins.
- Develop methods to estimate storage needs for transport digital twins depending on factors such as data retention, data variety, data granularity, data redundancy and scale of deployment – city-wide, regional, national.
- Develop methods to estimate the computing power necessary to run a transport digital twin, depending on factors such as data volume, data complexity, spatial and temporal resolution and scale of deployment – city-wide, regional, national.
- Build collaborative groups and communities, facilitate ongoing engagement between government, private sector, public utilities, building owners, community groups and citizens.
- Capture and share best practices and lessons learned from digital twin case studies globally.

10. Literature

10.1. Chapter 2 - WP1

Allen, B. D. (2021). *Digital Twins and Living Models at NASA*. NASA. Retrieved 25/09/2023 from ￼

Atos. (2023). *Tech Trends Radar: Key technologies and what they'll do to your business*. Atos. Retrieved 27/09/2023 from ￼

Attaran, M., & Celik, B. G. (2023). Digital Twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, *6*, 100165. ￼

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. *IEEE Access*, *7*, 167653-167671. ￼

Deloitte. (2023). *What is decarbonisation? The importance of decarbonisation explained*. Deloitte. Retrieved 27/10/2023 from ￼

EEA. (2023). Transport and environment report 2022 Digitalisation in the mobility system: challenges and opportunities. *European Environment Agency*, 1-218. ￼

Glaessgen, E., & Stargel, D. (2012). *The digital twin paradigm for future NASA and US Air Force vehicles* 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA, ￼

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Fumerfelt, & A. Alves (Eds.), *Transdisciplinary perspectives on complex systems: New findings and approaches* (pp. 85-113). Springer. ￼

Guerrero-Ibáñez, J., Zeadally, S., & Contreras-Castillo, J. (2018). Sensor Technologies for Intelligent Transportation Systems. *Sensors (Basel)*, *18*(4). ￼

Guerrero-Ibanez, J. A., Zeadally, S., & Contreras-Castillo, J. (2015). Integration challenges of intelligent transportation systems with connected vehicle, cloud computing, and internet of things technologies. *IEEE Wireless Communications*, *22*(6), 122-128. ￼

HWU. (2019). *Smart technology could hold key to safer winter roads*. Herriot Watt University. Retrieved 04/10/2023 from ￼

IIC. (2020). *Digital Twins for Industrial Applications. Definition, Business Values, Design Aspects, Standards and Use Cases* Industrial Internet Consortium (IIC). ￼

IoTNOW. (2018). *Stage Intelligence deploys AI platform in Helsinki to grow bike share scheme*. IoTNOW. Retrieved 27/10/2023 from ￼

Jiang, H., & Jiang, A. (2022). Monitoring System for the Construction of Arch Cover Method Subway Station Based on DT and IoT. *Journal of Sensors*, *2022*, 1875196. ￼

Kovacs, E., & Mori, K. (2023). Digital Twin Architecture – An Introduction. In N. Crespi, A. T. Drobot, & R. Minerva (Eds.), *The Digital Twin* (pp. 125-151). Springer International Publishing. ￼

Li, L., Aslam, S., Wileman, A., & Perinpanayagam, S. (2022). Digital Twin in Aerospace Industry: A Gentle Introduction. *IEEE Access*, *10*, 9543-9562. ￼

Perno, M., Hvam, L., & Haug, A. (2022). Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers. *Computers in Industry*, *134*, 103558. ￼

Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., Wang, L., & Nee, A. Y. C. (2021). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems*, *58*, 3-21. ￼

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers. *IEEE Access*, *8*, 21980-22012. ￼

Rolls-Royce. (2023). *Digital Twin. The advanced data-driven models set to power the future*. Rolls-Royce. Retrieved 27/10/2023 from ￼..

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital Twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration*, *30*, 100383. ￼

UN. (n.d.). *The Paris Agreement*. United Nations. Retrieved 18/10/2023 from ￼

Uri, J. (2020). *50 Years Ago: "Houston, We've Had a Problem"*. NASA. Retrieved 18/10/2023 from ￼

Wang, Z., Gupta, R., Han, K., Wang, H., Ganlath, A., Ammar, N., & Tiwari, P. (2022). Mobility Digital Twin: Concept, Architecture, Case Study, and Future Challenges. *IEEE Internet of Things Journal*, *9*(18), 17452-17467.

10.2. Chapter 3 - WP2

Aheleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. (2021). Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model. *Advanced Engineering Informatics*, *47*, 101225. https://doi.org/10.1016/j.aei.2020.101225

Attaran, M., & Celik, B. G. (2023). Digital Twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, *6*, 100165. https://doi.org/10.1016/j.dajour.2023.100165

Bianzino, N. M., & Yonge, J. d. (2022). *Metaverse: Could creating a virtual world build a more sustainable one?* Ernst & Young. Retrieved 16/10/2023 from https://www.ey.com/en_se/digital/metaverse-could-creating-a-virtual-world-build-a-more-sustainable-one

Botín-Sanabria, D. M., Mihaita, A.-S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. d. J. (2022). Digital twin technology challenges and applications: A comprehensive review. *Remote Sensing*, *14*(6), 1335. https://doi.org/10.3390/rs14061335

Burak, A. (2023). Harnessing Digital Twins in Logistics: The Future of Supply Chain Management. Retrieved 21/09/2023, from https://relevant.software/blog/digital-twins-in-logistics-the-future-of-supply-chain-management/

Couraud, B., Andoni, M., Robu, V., Norbu, S., Chen, S., & Flynn, D. (2023). Responsive FLEXibility: A smart local energy system. *Renewable and Sustainable Energy Reviews*, *182*, 113343. https://doi.org/10.1016/j.rser.2023.113343

Dohrmann, K., Gesing, B., & Ward, J. (n.d.). *Digital Twins in Logistics*. DHL Customer Solutions & Innovation. Retrieved 21/09/2023 from https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf

Fender, K. (2017). *Deutsche Bahn is targeting expansion of its long-distance operations in Germany thanks to two new fleets of trains*. Modern Railways. Retrieved 17/10/2023 from https://www.modernrailways.com/article/enter-ice4#:~:text=In%202011%20DB%20placed%20an,ICE4%20by%20DB%20in%202015.

Gabory, C. (2023). *Digital decarbonization: how digital twins are paving the way to a more sustainable, carbon-neutral world*. Engie. Retrieved 15/10/2023 from https://www.engie-deutschland.de/en/magazine/digital-decarbonization-how-digital-twins-are-paving-way-more-sustainable-carbon-neutral

Hasan, M. (2023). *Decoding Digital Twins: Exploring the 6 main applications and their benefits*. IOT Analytics. https://iot-analytics.com/6-main-digital-twin-applications-and-their-benefits/

Helbing, D., & Sánchez-Vaquerizo, J. A. (2023). Digital twins: potentials, ethical issues and limitations. In *Handbook on the politics and governance of Big Data and Artificial Intelligence* (pp. 64-104). Edward Elgar Publishing. https://doi.org/10.2139/ssrn.4167963

Ibrion, M., Paltrinieri, N., & Nejad, A. R. (2019). On risk of digital twin implementation in marine industry: Learning from aviation industry. *Journal of Physics: Conference Series*, *1357*(1), 012009. https://doi.org/10.1088/1742-6596/1357/1/012009

Katzir, R. (2023). *Digital Twins as a Service (DTaaS): What the SaaS is All About?* Medium. Retrieved 15/10/2023 from https://medium.com/@ran_katzir/digital-twins-what-the-saas-is-all-about-85ea1cb92971#:~:text=Digital%20Twin%20as%20a%20Service%20(DTaaS)%20is%20software%20that%20runs,directly%20over%20the%20mobile%20network.

Kuguoglu, B. K., van der Voort, H., & Janssen, M. (2021). The Giant Leap for Smart Cities: Scaling Up Smart City Artificial Intelligence of Things (AIoT) Initiatives. *Sustainability*, *13*(21), 12295. https://www.mdpi.com/2071-1050/13/21/12295

Li, L., Aslam, S., Wileman, A., & Perinpanayagam, S. (2022). Digital Twin in Aerospace Industry: A Gentle Introduction. *IEEE Access*, *10*, 9543-9562. https://doi.org/10.1109/ACCESS.2021.3136458

Mangan, T. (2020). *How Digital Twin Technology is Helping Build a Smart Railway System in Italy*. Nutanix. https://www.nutanix.com/theforecastbynutanix/industry/how-digital-twin-technology-is-helping-build-a-smart-railway-system-in-italy

Marcucci, E., Gatta, V., Le Pira, M., Hansson, L., & Bråthen, S. (2020). Digital twins: A critical discussion on their potential for supporting policy-making and planning in urban logistics. *Sustainability*, *12*(24), 10623. https://doi.org/10.3390/su122410623

McMahon, C. (2022). *The ROI of Digital Twin for Industrial Companies*. Retrieved 12/10/2023 from https://www.ptc.com/en/blogs/corporate/roi-of-digital-twin-for-industrial-companies

Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M., & Scapolo, F. (2022). *Towards a green and digital future*. Publications Office of the European Union. https://doi.org/10.2760/54

Murray, L. (2022). *How to decarbonise cities using digital twins*. Retrieved 15/10/2023 from https://eandt.theiet.org/content/articles/2022/07/how-to-decarbonise-cities-using-digital-twins/

Psarommatis, F., & May, G. (2023). A standardized approach for measuring the performance and flexibility of digital twins. *International Journal of Production Research*, *61*(20), 6923-6938. https://doi.org/10.1080/00207543.2022.2139005

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers. *IEEE Access*, *8*, 21980-22012. https://doi.org/10.1109/ACCESS.2020.2970143

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital Twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration*, *30*, 100383. https://doi.org/10.1016/j.jii.2022.100383

Tomych, I. (2023). *20 Digital Twins Companies*. DashDevs. Retrieved 15/10/2023 from https://dashdevs.com/blog/product-owner-talks-20-digital-twins-service-companies/

Tzachor, A., Sabri, S., Richards, C. E., Rajabifard, A., & Acuto, M. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nature Sustainability*, *5*(10), 822-829. https://doi.org/10.1038/s41893-022-00923-7

Wang, Z., & Lin, B. (2022). A Digital Twin enabled Maritime Networking Architecture. 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), 1-5. https://doi.org/10.1109/VTC2022-Spring54318.2022.9860929

10.3. Chapter 4 - WP3

Automatic Outlier Detection - Hydrosphere.io. (n.d.). Hydrosphere.io. Retrieved October 29, 2023, from https://docs.hydrosphere.io/about/hydrosphere-features/automatic-outlier-detection#:~:text=Anomaly%20detection%20is%20focused%20on

Baasch, B., Roth, M., & Groos, J. (2018). In-service condition monitoring of rail tracks: On an on-board low-cost multi-sensor system for condition based maintenance of railway tracks. *Internationales Verkehrswesen*, *70*(1), 76–79. https://core.ac.uk/reader/154791780

Bertoncello, M., Martens, C., Möller, T., & Schneiderbauer, T. (2021, February 11). *Unlocking full value from data from connected cars | McKinsey*. Www.mckinsey.com. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/unlocking-the-full-life-cycle-value-from-connected-car-data

Carpenter, T., & Pyles, J. (2011). *Microsoft SharePoint 2010 Administration*. John Wiley & Sons.

Castro, D. (2021, November 29). *Improving Consumer Welfare with Data Portability*. Center for Data Innovation. https://datainnovation.org/2021/11/improving-consumer-welfare-with-data-portability/

Censis. (2017). *Delivering "Doctor Diesel."* CENSIS. https://censis.org.uk/censis_projects/icon-research/

Chen, X., Kang, E., Shiraishi, S., Preciado, V. M., & Jiang, Z. (2018). Digital Behavioral Twins for Safe Connected Cars. *Proceedings of the 21th ACM/IEEE International Conference on Model Driven Engineering Languages and Systems*. https://doi.org/10.1145/3239372.3239401

Dave, D. (2023, October 12). *What are the best practices for creating and managing digital twins of IoT devices?* Www.linkedin.com. https://www.linkedin.com/advice/0/what-best-practices-creating-managing-digital-1f

Digital Twins in Logistics - A DHL perspective on the impact of digital twins on the logistics industry. (n.d.). In *https://www.dhl.com/* (pp. 1–39). Retrieved October 29, 2023, from https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf

Disruptive Engineering next-generation road sensors for sustainable transport. (n.d.). Businessnorway.com. Retrieved October 29, 2023, from https://businessnorway.com/solutions/disruptive-engineering-next-generation-road-sensors-for-sustainable-transport

ESRG Releases OstiaEdge Monitoring. (2009, February 6). MarineLink. https://www.marinelink.com/news/monitoring-ostiaedge329606

European Automobile Manufacturers Association. (2020). CO2 emissions from heavy-duty vehicles Preliminary CO2 baseline (Q3-Q4 2019) estimate. In *www.acea.be* (pp. 1–11). European Automobile Manufacturers Association. https://www.acea.auto/files/ACEA_preliminary_CO2_baseline_heavy-duty_vehicles.pdf.

Fong, B., Rapajic, P. B., Hong, G. Y., & Fong, A. C. M. (2003). Factors causing uncertainties in outdoor wireless wearable communications. *IEEE Pervasive Computing*, *2*(2), 16–20. https://doi.org/10.1109/mprv.2003.1203748

Fowler, G. A. (2019, December 17). Perspective | What does your car know about you? We hacked a Chevy to find out. *Washington Post*. https://www.washingtonpost.com/technology/2019/12/17/what-does-your-car-know-about-you-we-hacked-chevy-find-out/

Grace, B. (2016, August 12). *Local Motors Unveils Olli, the Self-Driving Urban Minibus with Street Smarts*. Prospector Knowledge Center. https://www.ulprospector.com/knowledge/4896/pe-local-motors-unveils-olli/

Guidance on the AI auditing framework Draft guidance for consultation 20200214 Version 1.0 2 AI auditing framework -draft guidance for consultation (p. 1=105). (2020). https://ico.org.uk/media/2617219/guidance-on-the-ai-auditing-framework-draft-for-consultation.pdf

Hamed, N., Rana, O., Orozco-Terwengel, P., Goossens, B., & Perera, C. (2022). *OPEN DATA OBSERVATORIES*. https://orca.cardiff.ac.uk/140048/21/NAEIMA_PAPER01_SEP_2022_V22__ORCA_%20%283%29.pdf

Han, T., & Ansari, N. (2015). RADIATE: radio over fiber as an antenna extender for high-speed train communications. *IEEE Wireless Communications*, *22*(1), 130–137. https://doi.org/10.1109/mwc.2015.7054728

Hatt, T. (2022). *Industry pathways to net zero - decarbonisation in transport*. Gsmaintelligence.com; GSM Association. https://data.gsmaintelligence.com/api-web/v2/research-file-download?id=69042321&file=070322-Industry-Pathways-Transport.pdf

He, Z., Hu, J., Park, B. B., & Levin, M. W. (2019). Vehicle sensor data-based transportation research: Modeling, analysis, and management. *Journal of Intelligent Transportation Systems*, *23*(2), 99–102. https://doi.org/10.1080/15472450.2019.1586335

Henderson, T. (2022, August 10). *Digital Twin or White Elephant?* KPMG. https://kpmg.com/uk/en/blogs/home/posts/2022/07/digital-twin-or-white-elephant.html#:~:text=Good%20quality%20data%20is%20essential

How can artificial intelligence help build a greener future? (2023, March 15). Thales Group. https://www.thalesgroup.com/en/worldwide/group/magazine/how-can-artificial-intelligence-help-build-greener-future

Integrated Airports. (n.d.). Arcadis.com. Retrieved October 29, 2023, from https://www.arcadis.com/en-gb/expertise/solutions/mobility/integrated-airports?

Kono, V. (2021, August 12). *TfGM to spearhead Active Travel development in Manchester*. VivaCity. https://vivacitylabs.com/tfgm-active-travel-scheme

Kumar, S. A. P., Madhumathi, R., Chelliah, P. R., Tao, L., & Wang, S. (2018). A novel digital twin-centric approach for driver intention prediction and traffic congestion avoidance. *Journal of Reliable Intelligent Environments*, *4*(4), 199–209. https://doi.org/10.1007/s40860-018-0069-y

Lag, S., Vartdal, B.-J., & Knutsen, K. (2015). *SHIP CONNECTIVITY = DNV GL STRATEGIC RESEARCH & INNOVATION POSITION PAPER* (pp. 1–48). https://www.dnv.com/Images/DNV%20GL%20-%20Ship%20Connectivity_tcm8-56026.pdf

meShare. (2023, May). *Key Considerations When Deciding Whether to Deploy IoT in Your Business*. Www.linkedin.com. https://www.linkedin.com/pulse/key-considerations-when-deciding-whether-deploy-iot-your-business

Metadata, Data Models and Interoperability. (n.d.). Retrieved October 29, 2023, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1086099/economic-data-innovation-fund-metadata-data-models-and-interoperability-summary-paper.pdf

Middleton, S. (2023, June 6). *API Design Guidelines: Essential Elements*. Www.linkedin.com. https://www.linkedin.com/pulse/api-design-guidelines-essential-elements-scott-middleton

New Measurement Train (NMT). (n.d.). Network Rail. Retrieved October 29, 2023, from https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/our-fleet-machines-and-vehicles/new-measurement-train-nmt

New Mobility. (n.d.). Arcadis.com. Retrieved October 29, 2023, from https://www.arcadis.com/en-gb/expertise/solutions/mobility/new-mobility

Nolle, T. (2019, July 30). *Demystify IoT compliance with 3 considerations | TechTarget*. IoT Agenda. https://www.techtarget.com/iotagenda/tip/Demystify-IoT-compliance-with-3-considerations

O'Brien, K. (2023, May 23). *What is smart transportation?* IBM Blog. https://www.ibm.com/blog/smart-transportation/

Pan, S., Zhong, R. Y., & Qu, T. (2019). Smart product-service systems in interoperable logistics: Design and implementation prospects. *Advanced Engineering Informatics*, *42*, 100996. https://doi.org/10.1016/j.aei.2019.100996

Patnaik, A. (2023, August 16). *Components of Digital Twins: Unveiling the Inner Workings*. Www.linkedin.com. https://www.linkedin.com/pulse/industry-40-syncing-future-synergy-between-digital-part-amar-patnaik-1f

Providing equitable convenient transit with The LA Metro Regional Connector. (n.d.). Www.arcadis.com. Retrieved October 29, 2023, from https://www.arcadis.com/en-gb/projects/north-america/united-states/providing-equitable-convenient-transit-with-the-la-metro-regional-connector?_gl

Rolls-Royce celebrates 50th anniversary of Power-by-the-Hour. (2012, October 30). Rolls-Royce.com. https://www.rolls-royce.com/media/press-releases-archive/yr-2012/121030-the-hour.aspx

Shahat, E., Hyun, C. T., & Yeom, C. (2021). City Digital Twin Potentials: A Review and Research Agenda. *Sustainability*, *13*(6), 3386. https://doi.org/10.3390/su13063386

Shakib, T. (2019, October 29). *Maersk tracks goods across the planet with Microsoft Azure IoT*. Www.linkedin.com. https://www.linkedin.com/pulse/maersk-tracks-goods-across-planet-microsoft-azure-iot-tony-shakib

Smart Mobility: Main elements of growing a platform business. (2023, August 23). Intellias. https://intellias.com/smart-mobility-ecosystem/

Smith, S. (2022). *Consumer Connected Car Revenues to near $50bn by 2022, with Half of Vehicles Connected Globally*. Juniperresearch.com. https://www.juniperresearch.com/press/consumer-connected-car-revenues-near-50bn-2022

Song, H., Srinivasan, R., Sookoor, T., & Jeschke, S. (2017). *Smart Cities: Foundations, Principles, and Applications* (pp. 1–912). Wiley. https://www.wiley.com/en-gb/Smart+Cities%3A+Foundations%2C+Principles%2C+and+Applications-p-9781119226444

Swart, S. (2017, April 6). *Eclipse Ditto*. Projects.eclipse.org. https://projects.eclipse.org/projects/iot.ditto

Tagiew, R., Köppel, M., Schwalbe, K., Denzler, P., Neumaier, P., Klockau, T., Boekhoff, M., Klasek, P., & Tilly, R. (2023). OSDaR23: Open Sensor Data for Rail 2023. In *https://arxiv.org/*. https://arxiv.org/pdf/2305.03001.pdf

Technology at Maersk. (n.d.). Www.maersk.com. Retrieved October 29, 2023, from https://www.maersk.com/about/technology

The Internet of Trains. (n.d.). In *https://www.teradata.com/*. Retrieved October 29, 2023, from https://assets.teradata.com/resourceCenter/downloads/CaseStudies/EB8903.pdf?processed=1

Valich, T. (2015, May 8). *Big Data in Planes: P&W GTF Engine to create 10GB/s*. VR World. https://vrworld.com/2015/05/08/big-data-in-planes-new-pw-gtf-engine-telemetry-to-generate-10gbs/

Virta. (2023). *Vehicle-to-Grid (V2G): Everything you need to know*. www.virta.global. https://www.virta.global/vehicle-to-grid-v2g

Wang, J., Ye, L., Gao, R. X., Li, C., & Zhang, L. (2018). Digital Twin for rotating machinery fault diagnosis in smart manufacturing. *International Journal of Production Research*, *57*(12), 3920–3934. https://doi.org/10.1080/00207543.2018.1552032

Wang, Z., Gupta, R., Han, K., Wang, H., Ganlath, A., Ammar, N., & Tiwari, P. (2022). Mobility Digital Twin: Concept, Architecture, Case Study, and Future Challenges. *IEEE Internet of Things Journal*, 1–1. https://doi.org/10.1109/jiot.2022.3156028

Wang, Z., Liu, L., Zhou, M., & Ansari, N. (2008). A Position-Based Clustering Technique for Ad Hoc Intervehicle Communication. *IEEE Transactions on Systems, Man, and Cybernetics, Part c (Applications and Reviews)*, *38*(2), 201–208. https://doi.org/10.1109/TSMCC.2007.913917

What is "Data Interoperability?" (n.d.). The Data Interoperability Standards Consortium. Retrieved October 29, 2023, from https://datainteroperability.org/

Wikipedia Contributors. (2019, August 16). *Technical standard*. Wikipedia; Wikimedia Foundation. https://en.wikipedia.org/wiki/Technical_standard

10.4. Chapter 5 - WP4

AAG. (2023). The latest cloud computing statistics. Link

Alamouti, S. M., Arjomandi, F., & Burger, M. (2022). Hybrid Edge Cloud: A Pragmatic Approach for Decentralized Cloud Computing. IEEE Communications Magazine, 60(9), 16-29. https://doi.org/10.1109/MCOM.001.2200251

Arif, A., Barrigon, F. A., Gregoretti, F., et al. (2020). Performance and energy-efficient implementation of a smart city application on FPGAs. J Real-Time Image Proc, 17, 729-743. https://doi.org/10.1007/s11554-018-0792-x

Attaran, M., et al. (2023). Digital twin: benefits, use cases, challenges, and opportunities. Decision Analytics Journal, 6. https://doi.org/10.1016/j.dajour.2023.100165

Botin-Sanabria, D.M., et al. (2022). Digital twin technology challenges and applications: a comprehensive review. Remote Sensing, 14(6). https://doi.org/10.3390/rs14061335

Compare the Cloud. (2023). Why a digital twin graph will help manage real-world complexity at scale. Retrieved October 29, 2023, from https://www.comparethecloud.net/business/why-a-digital-twin-graph-will-help-manage-real-world-complexity-at-scale/

Davenport, Thomas H., Redman, Thomas C. (2022). How AI Is Improving Data Management. Sloan Review. Retrieved October 29, 2023, from https://sloanreview.mit.edu/article/how-ai-is-improving-data-management/

Expero Inc. (2023). What is a digital twin? Retrieved October 29, 2023, from https://www.experoinc.com/expero-resources/data-and-digital-twins

Ferre-Bigorra, J., et al. (2022). The adoption of urban digital twins. Cities, 131. https://doi.org/10.1016/j.cities.2022.103905

Green Algorithms. https://www.green-algorithms.org/

Green Software Foundation. https://greensoftware.foundation/

Holliman, S., et al. (2019). Petascale Cloud Supercomputing for Terapixel Visualization of Digital Twin. IEEE Transactions on Cloud Computing, 10(1), 583-594. https://doi.org/10.1109/TCC.2019.2958087

Kaklis, D., et al. (2023). Enabling digital twins in the maritime sector through the lens of AI and industry 4.0. International Journal of Information Management Data Insights, 3. https://doi.org/10.1016/j.jjimei.2023.100178

Knebel, F., et al. (2023). A study on cloud and edge computing for the implementation of digital twins in the oil & gas industries. Computers & Industrial Engineering, 182. https://doi.org/10.1016/j.cie.2023.109363

Lannelongue, L., et al. (2023). Greener principles for environmentally sustainable computational science. Nature Computational Science, 3, 514-521. https://doi.org/10.1038/s43588-023-00461-y

Mainroads Western Australia (2022). Intelligent transport systems (ITS) master plan. Retrieved October 29, 2023, from https://www.mainroads.wa.gov.au/globalassets/technical-commercial/technical-library/electrical-and-its-standards-engineering/intelligent-transport-systems-its-master-plan-2022-2030.pdf?v=49bfae

Neves, A., & Brand, C. (2019). Assessing the potential for carbon emissions savings from replacing short car trips with walking and cycling using a mixed GPS-travel diary approach. Transportation Research Part A: Policy and Practice, 123, 130-146. https://doi.org/10.1016/j.tra.2018.08.022

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital Twins: State of the art theory and practice, challenges, and open research questions. Journal of Industrial Information Integration, 30, 100383. https://doi.org/10.1016/j.jii.2022.100383

Statistica (2017). Big data on wheels. Retrieved October 29, 2023, from https://www.statista.com/chart/8018/connected-car-data-generation/

TRIB Roadmap. https://trib.org.uk/roadmap

Wang, Z., et al. (2022). Mobility digital twin: concept, architecture, case study, and future challenges. IEEE Internet of Things Journal, 9(18). https://doi.org/10.1109/JIOT.2022.3156028

Weifei Hu, et al. (2021). Digital twin: a state-of-the-art review of its enabling technologies, applications and challenges. Journal of Intelligent Manufacturing and Special Equipment, 2(1). https://doi.org/10.1108/JIMSE-12-2020-010

Weil, C., et al. (2023). Urban digital twin challenges: a systematic review and perspectives for sustainable smart cities. Sustainable Cities and Society, 99. https://doi.org/10.1016/j.scs.2023.104862

Yao, J-F., et al. (2023). Systematic review of digital twin technology and applications. Visual Computing for Industry, Biomedicine, and Art, 6(10). https://doi.org/10.1186/s42492-023-00137-4

Zhihan, L., & Shang, W. (2023). Impacts of intelligent transportation systems on energy conservation and emission reduction of transport systems: a comprehensive review. Green Technologies and Sustainability, 1(1). https://doi.org/10.1016/j.grets.2022.100002

10.5. Chapter 6 - WP5

Attaran, M., Gokhan Celik, B. (2023). Digital Twin: Benefits, use cases, challenges, and opportunities. Decision Analytics, 6. https://doi.org/10.1016/j.dajour.2023.100165

Barrett, B. (2020, February 3). An Artist Used 99 Phones to Fake a Google Maps Traffic Jam. WIRED. https://www.wired.com/story/99-phones-fake-google-maps-traffic-jam/

C. Alcaraz and J. Lopez. (2022) Digital Twin: A Comprehensive Survey of Security Threats. IEEE Communications Surveys & Tutorials, 24(3) 1475-1503. https://doi.org/10.1109/COMST.2022.3171465

Centre for Digital Built Britain. (2018). The Gemini Principals. https://www.cdbb.cam.ac.uk/system/files/documents/TheGeminiPrinciples.pdf

Centre for Digital Built Britain. (2021). The pathway towards an Information Management Framework (IMF). https://www.cdbb.cam.ac.uk/files/approach_summaryreport_final.pdf

Eckhart, M., Ekelhart, A. (2019). Digital Twins for Cyber-Physical Systems Security: State of the Art and Outlook. In: Biffl, S., Eckhart, M., Lüder, A., Weippl, E. (eds) Security and Quality in Cyber-Physical Systems Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-25312-7_14

Energy Systems Catapult. (2022). BEIS Energy System Digital Twin Demonstrator. https://es.catapult.org.uk/wp-content/uploads/2022/08/BEIS-Energy-System-Digital-Twin-Demonstrator-Report_FINAL.pdf

Erol, T., Mendi, A. F., Doğan, D. (2020). Digital Transformation Revolution with Digital Twin Technology. 4th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Istanbul, Turkey, 2020, (pp. 1-7). IEEE. https://doi.org/10.1109/ISMSIT50672.2020.9254288

Goldbaum, C., Rashbaum W. (2021, June 21). "The M.T.A. Is Breached by Hackers as Cyberattacks Surge". New York Times. https://www.nytimes.com/2021/06/02/nyregion/mta-cyber-attack.html

Hippold, S. (2019, January 23). How Digital Twins Simplify the IoT. Gartner. https://www.gartner.com/smarterwithgartner/how-digital-twins-simplify-the-iot

Industry IoT Consortium and Digital Twin Consortium. (2022). IoT Security Maturity Model Digital Twin Profile. https://www.digitaltwinconsortium.org/wp-content/uploads/sites/3/2022/06/SMM-Digital-Twin-Profile-2022-06-20.pdf

International Organization for Standardization. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 5: Security-minded approach to information management (ISO 19650-5:2020). https://www.iso.org

International Organization for Standardization. (2021). Automation systems and integration — Digital twin framework for manufacturing (ISO 23247-1:2021). https://www.iso.org

IPC International, (2020). International Standard for Digital Twins (IPC-2551). https://www.ipc.org

Kolias, C., Kambourakis, G., Stavrou, A., Voas, J. (2017). DDoS in the IoT: Mirai and Other Botnets, Computer, 50(7), 80-84. https://doi.org/10.1109/MC.2017.201

Langner, R., (2011). Stuxnet: Dissecting a Cyberwarfare Weapon. IEEE Security & Privacy, 9(3), 49-51. https://doi.org/10.1109/MSP.2011.67

M. Jafari, A. Kavousi-Fard, T. Chen and M. Karimi. (2023). A Review on Digital Twin Technology in Smart Grid, Transportation System and Smart City: Challenges and Future. IEEE Access, 11, 17471-17484. https://doi.org/10.1109/ACCESS.2023.3241588

National Grid ESO (2022) Virtual Energy System Programme Strategy Update August 2022. https://www.nationalgrideso.com/document/266076/download

National Institute of Standards and Technology (NIST). (2021). (DRAFT) Considerations for Digital Twin Technology and Emerging Standards (NIST IR 8356). https://nvlpubs.nist.gov/nistpubs/ir/2021/NIST.IR.8356-draft.pdf

Suhail, S., Hussain, R., Jurdak, R. (2023). Security Attacks and Solutions for Digital Twins. arXiv. https://doi.org/10.48550/arXiv.2202.12501

The British Standards Institution, (2022). Built environment. Digital twins overview and principles (BSI Flex 260: V1.0 2022-01). https://www.bsigroup.com/

The Change2Twin Consortium. (2021), First report on standards relevant for digital twins. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5dab9d442&appId=PPGMS

University of Strathclyde. (2023, May 23). 'Digital twin' project will inform future innovation in the UK energy industry. https://www.strath.ac.uk/whystrathclyde/news/2023/digitaltwinprojectwillinformfutureinnovationintheukenergyindustry/

Wang, K., Wang, Y., Li, Y. et al. (2022), A review of the technology standards for enabling digital twin [version 2]. Digital Twin, 2:4. https://doi.org/10.12688/digitaltwin.17549.2

10.6. Chapter 7 – WP6

Admin. (2018). *NUS creates 'digital twin' of Singapore's next gen port*. Manifold Times. Retrieved 23/09/2023 from https://www.manifoldtimes.com/news/insight-exclusive-nus-creates-digital-twin-of-singapores-next-gen-port/

Bills, T. (2021). San Francisco Airport's Dynamic Twin Has Transformed Operations. Retrieved 21/09/2023, from https://www.esri.com/about/newsroom/blog/san-francisco-airport-bim-gis-processes/

Bischofberger, C. (2022). Digital twins and the smart grid. Retrieved 22/09/2023, from https://etech.iec.ch/issue/2022-03/digital-twins-and-the-smart-grid

Boyles, R. (2019). *How the Port of Rotterdam is using IBM digital twin technology to transform itself from the biggest to the smartest*. IBM Blog. Retrieved 10/10/2023 from https://www.ibm.com/blog/iot-digital-twin-rotterdam/

Burak, A. (2023). Harnessing Digital Twins in Logistics: The Future of Supply Chain Management. Retrieved 21/09/2023, from https://relevant.software/blog/digital-twins-in-logistics-the-future-of-supply-chain-management/

Camus, A. (2023). Singapore Land Authority Develops Digital Twin of all Public Roads. *Geo Weks News*. Retrieved 25/09/2023, from https://www.geoweeknews.com/news/singapore-land-authority-digital-twin-bentley-systems-3d-mapping

Carey, C. (2022). *Digital twin helps Stuttgart to measure sustainability*. CitiesToday. Retrieved 10/10/2023 from https://cities-today.com/digital-twin-helps-stuttgart-to-measure-sustainability/

Catapult. (2022). *BEIS Energy Systems. Digital Twin Demonstrator*. Retrieved 22/09/2023 from https://es.catapult.org.uk/project/energy-system-digital-twin-demonstrator-project/

Dohrmann, K., Gesing, B., & Ward, J. (n.d.). *Digital Twins in Logistics*. DHL Customer Solutions & Innovation. Retrieved 21/09/2023 from https://www.dhl.com/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf

Garcia Agis, J. J., Brett, P. O., Erikstad, S. O., & Gaspar, H. (2022). Reshaping Digital Twin in Technology Developments for Enhancing Marine Systems Design. *SNAME 14th International Marine Design Conference*, *Day 3 Tue, June 28, 2022*. https://doi.org/10.5957/imdc-2022-268

Gartner. (2023). *Supply Chain Technologies and Digital Transformation*. Gartner. Retrieved 10/10/2023 from https://www.gartner.com/en/supply-chain/topics/supply-chain-digital-transformation

Giering, J.-E., & Dyck, A. (2021). Maritime Digital Twin architecture. *A concept for holistic Digital Twin application for shipbuilding and shipping*, *69*(12), 1081-1095. https://doi.org/10.1515/auto-2021-0082

He, P., Almasifar, N., Mehbodniya, A., Javaheri, D., & Webber, J. L. (2022). Towards green smart cities using Internet of Things and optimization algorithms: A systematic and bibliometric review. *Sustainable Computing: Informatics and Systems*, *36*, 100822. https://doi.org/https://doi.org/10.1016/j.suscom.2022.100822

Hinz, T., Mazerski, G., Krishnan, A., Molchanov, B., Elg, M., & Wejberg, V. (2023). *Digital Twin for Evaluation of Emission Reduction by Novel Technologies* 22nd Conference on Computer Applications and Information Technology in the Maritime Industries, Drübeck / Germany.

Jung, B., Haag, D., Strobl, P., & Weichert, L. (2022). *Back on track: Solving the digitization challenge for Europe's rail sector*. PwC. Retrieved 20/10/2023 from https://www.strategyand.pwc.com/de/en/industries/transport/railway-digitization/strategyand-railway-digitization.pdf

Kampczyk, A., & Dybeł, K. (2021). The Fundamental Approach of the Digital Twin Application in Railway Turnouts with Innovative Monitoring of Weather Conditions. *Sensors*, *21*(17), 5757. https://www.mdpi.com/1424-8220/21/17/5757

King, A. (2022). *Emissions-free sailing is full steam ahead for ocean-going shipping*. EU Commission Horizon. Retrieved 10/10/2023 from https://ec.europa.eu/research-and-innovation/en/horizon-magazine/emissions-free-sailing-full-steam-ahead-ocean-going-shipping

Laukotka, F. N., & Krause, D. (2023). Supporting Digital Twins for the Retrofit in Aviation by a Model-Driven Data Handling. *Systems*, *11*(3), 142. https://www.mdpi.com/2079-8954/11/3/142

Lee, J.-H., Nam, Y.-S., Kim, Y., Liu, Y., Lee, J., & Yang, H. (2022). Real-time digital twin for ship operation in waves. *Ocean Engineering*, *266*, 112867. https://doi.org/https://doi.org/10.1016/j.oceaneng.2022.112867

Li, L., Aslam, S., Wileman, A., & Perinpanayagam, S. (2022). Digital Twin in Aerospace Industry: A Gentle Introduction. *IEEE Access*, *10*, 9543-9562. https://doi.org/10.1109/ACCESS.2021.3136458

MPA. (2022). *Singapore Maritime Institute partners stakeholders in R&D collaborations to drive maritime digitalisation and artificial intelligence*. MPA Singapore. Retrieved 21/09/2023 from https://www.mpa.gov.sg/docs/mpalibraries/media-releases/2022/press-release---singapore-maritime-institute-forum-2022-2

Power by the hour. (2022). MRO Business Today. Retrieved 20/10/2023 from https://www.mrobusinesstoday.com/power-by-the-hour/

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital Twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration*, *30*, 100383. https://doi.org/10.1016/j.jii.2022.100383

Spinview. (2022). *Transport for London partners with digital-twin start-up Spinview to accelerate 2030 zero-carbon railway goals*. Spinview News. Retrieved 21/09/2023 from https://spinview.io/transport-for-london/

Sresakoolchai, J., & Kaewunruen, S. (2023). Railway infrastructure maintenance efficiency improvement using deep reinforcement learning integrated with digital twin based on track geometry and component defects. *Scientific Reports*, *13*(1), 2439. https://doi.org/10.1038/s41598-023-29526-8

Valerio, P. (2023). Largest UK Municipal Port Uses IoT and Digital Twins to Advance its Sustainability Retrieved 23/09/2023, from https://iot.eetimes.com/largest-uk-municipal-port-uses-iot-and-digital-twins-to-advance-its-sustainability/

Wolf, K., Dawson, R. J., Mills, J. P., Blythe, P., & Morley, J. (2022). Towards a digital twin for supporting multi-agency incident management in a smart city. *Scientific Reports*, *12*(1), 16221. https://doi.org/10.1038/s41598-022-20178-8

Wong, E. Y., Mo, D. Y., & So, S. (2021). Closed-loop digital twin system for air cargo load planning operations. *International Journal of Computer Integrated Manufacturing*, *34*(7-8), 801-813. https://doi.org/10.1080/0951192X.2020.1775299

Xu, B., Wang, J., Wang, X., Liang, Z., Cui, L., Liu, X., & Ku, A. Y. (2019). A case study of digital-twin-modelling analysis on power-plant-performance optimizations. *Clean Energy*, *3*(3), 227-234. https://doi.org/10.1093/ce/zkz025

Yeon, H., Eom, T., Jang, K., & Yeo, J. (2023). DTUMOS, digital twin for large-scale urban mobility operating system. *Scientific Reports*, *13*(1), 5154. https://doi.org/10.1038/s41598-023-32326-9

Yigit, Y., Nguyen, L. D., Ozdem, M., Kinaci, O. K., Hoang, T., Canberk, B., & Duong, T. Q. (2023). TwinPort: 5G drone-assisted data collection with digital twin for smart seaports. *Scientific Reports*, *13*(1), 12310. https://doi.org/10.1038/s41598-023-39366-1

Yuting, Z. (2022). Digital twin enhances Shanghai's transportation system. Shine. Retrieved 10/10/2023 from https://www.shine.cn/news/metro/2209050107/

TRANSIT
Esmée Fairbairn Building
Heriot-Watt University
Edinburgh EH14 4AS

info@transit.ac.uk

transit.ac.uk

CENSIS
Inovo Building
121 George St
Glasgow G1 1RD

info@censis.tech

censis.tech