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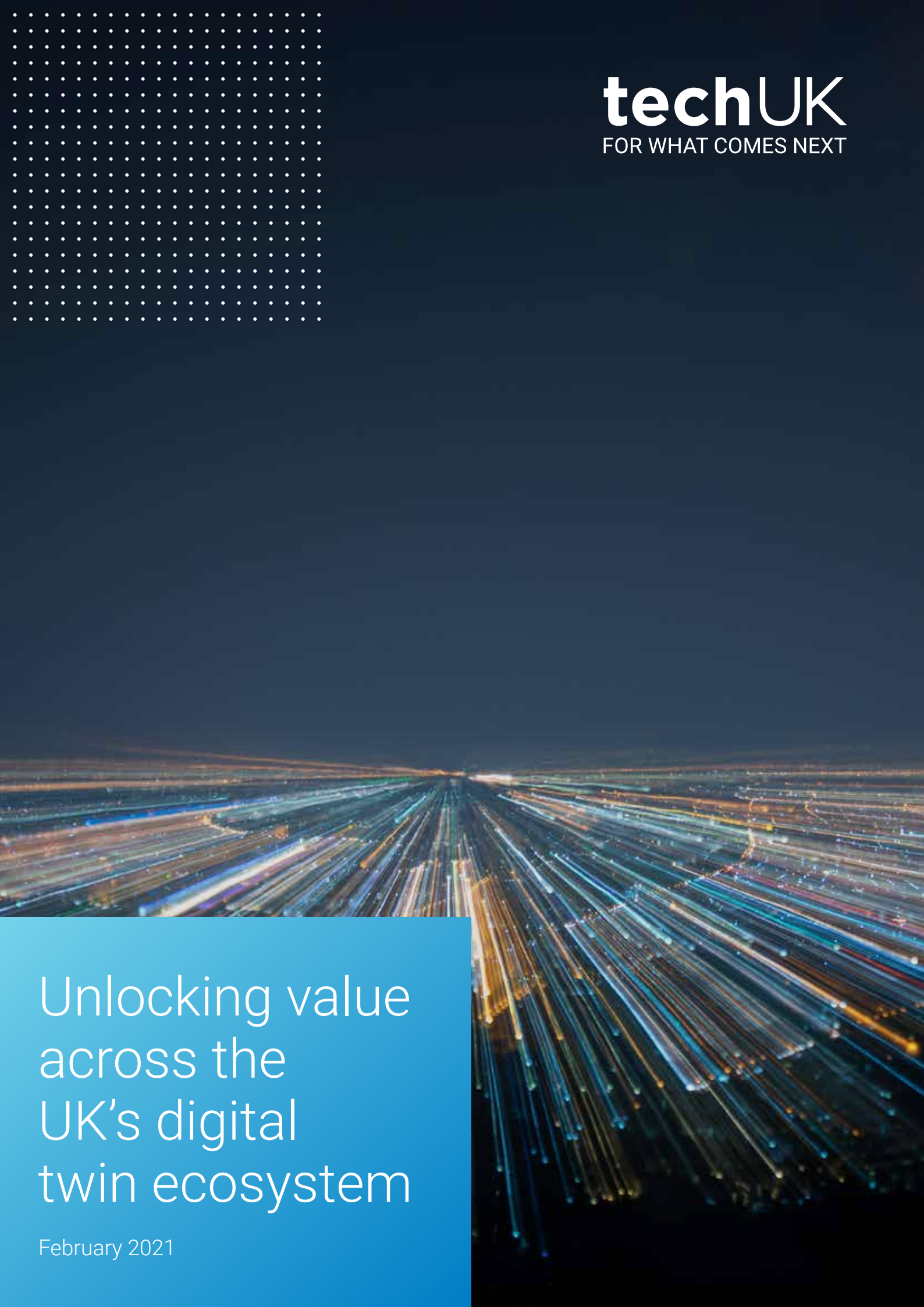

Unlocking value across the UK's digital twin ecosystem

February 2021

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1. Foreword | DTWG

Erwin Frank-Schultz
Chief Technology Officer (Energy, Environment and Utilities), IBM
Chair, Digital Twins Working Group, techUK

Neil Thompson
Director, Digital Construction, SNC Lavalin
Vice-chair, Digital Twins Working Group, techUK

A perfect storm has been created for digital twins. As we look towards the recovery of the global economy and reflecting on the task ahead of us in terms of climate change, we must focus on how our products, services and infrastructure are built and used. The acceleration of digitalisation driven by the pandemic and the urgency of net zero targets create a crisis we cannot waste.

Advanced manufacturing, generative design, 5G, cloud computing, artificial intelligence, wearable technologies, sensors, and many more are technologies that are converging for the first time and will enable the creation of digital twins.

These socio-technological dynamics motivated techUK to create the Digital Twins Working Group (DTWG) in March last year. The timing was almost perfect and brought together a broad spectrum of thought leaders from techUK members. We are very honoured to have been chosen as the Chair and Vice-chair of the DTWG and would like to thank our wider group members for their time, deep insight, and practical experience which they contributed under difficult circumstances. Much of this has been incorporated into the report which, in our view, provides an excellent basis and route-map for developing consistent and coherent digital twins.

Our mission was to connect and learn from leaders from a diverse range of backgrounds, from buildings, planes, trains, and Formula One cars, to jet engines, nuclear fusion reactors, and schools. This interdisciplinary focus enabled us to think about the full scale of the impact of digital twins which led to our close collaboration with the Centre for Digital Built Britain (CDBB) and the National Digital Twin Programme (NDTP).

We want you to join us on our journey to unite different industrial sectors through the implementation of digital twins. This document is only a starting point in the journey we need to go on take the opportunity and meet the challenge of the perfect storm we find ourselves in.

In closing, we want to thank Tom Henderson, from techUK, who's enthusiasm, persistence, diligence, and hard work have played a huge role in the delivery of this report which we can all take pride in.

2. Foreword | Cambridge Centre for Digital Built Britain

Mark Enzer OBE
Head of the National Digital Twin Programme

techUK sets out an inspiring vision of using digital twins for both value creation and public good across all sectors. This takes the vision of the National Digital Twin Programme and expands it beyond infrastructure, the built environment and across the economy. I believe this is the necessary direction of a nationally driven programme as connected digital twins can bring benefits to people across all sectors. techUK's application of digital twins to social inequality is particularly pertinent as we look to navigate our way out of this pandemic in the fairest way possible. Using digital twins to improve the quality of social housing will have tremendous impact across communities so that it is not just the hi-tech, digitally enabled communities that benefit. Using digital twins to get people safely back on public transport minimising harm to their own health and to the environment is essential as we plot a path to economic recovery and net zero. Imagine how our own personal digital twins could help us monitor our own health in the future.

The benefits from digital twins come from the insights they can provide, and the decisions we then make. Connecting digital twins across sectors will provide insights, enable analytics and the application of artificial intelligence to determine solutions to the systemic challenges we face, like climate change. But what is absolutely key to connecting digital twins is interoperability. A unique opportunity that we have In the National Digital Twin Programme is being able to discuss interoperability with the techUK Digital Twin working group. We value the dialogue because we recognise that there are multiple potential approaches, and we agree on the vision of connecting digital twins to improve social outcomes – a vision that this report strongly endorses.

We are working with techUK members to understand how point-to-point connections between digital twins can be integrated with the Information Management Framework (IMF), which will enable connections between digital twins at scale. We see how important it is to learn from different approaches to help the best models to emerge over time. Being able to get that insight from organisations developing and connecting digital twins in the here and now is incredibly important to making the National Digital Twin Programme work for all across industry, academia, and government.

I believe that connected digital twins are critical to the future success of the UK. Given our existing capability in information management, data science and artificial intelligence, we can invest in the future workforce to ensure we can leverage these skills to build and maintain a competitive advantage in digital twins on the world stage and at the same time creating high value jobs. It's a great collaborative ambition to achieve this and techUK's endorsement for Government funding of the UK's digital twin ecosystem is an important positive step towards realising the vision.

3. Foreword | techUK

Susanne Baker
Associate Director (Climate, Environment and Sustainability)
techUK

Tom Henderson
Programme Manager, Smart Infrastructure and Systems (Digital Twins and Smart Cities)
techUK

As the UK seeks to address severe patterns of social inequality, economic crisis, and climate change, accelerating the development, adoption, and diffusion of digital twins is rapidly becoming a national-level imperative.

The global proliferation of digital technologies has triggered the emergence of a vibrant digital twin ecosystem in the UK, and there are significant opportunities in the here-and-now to leverage digital twins to unlock value for our people, economy, society, and planet.

In this report, we show that digital twins can yield incremental environmental benefits as they are developed, and that they can be leveraged to encourage decarbonisation, facilitate closures and environmental remediation, and to de-risk and accelerate the integration of cutting-edge green technologies. In future, digital twins can play a key role in supporting the systems thinking needed to manage the complexity of net zero transition.

Moreover, as we zoom in on the role that digital twins could play in enabling the UK to build a fairer society and 'level-up' post-COVID, digital twins could play a central part in driving locally contextualised decision-making, in enhancing the efficacy of public spending and public services, and in driving connectivity upgrades between different regions.

Finally, we acknowledge that digital twins can help innovators to bring transformative applications to market by enabling faster, cheaper prototyping, turbo charging collaborative innovation and continuous evaluation, and strengthening research infrastructure and innovating at the limits.

Looking to the future our hope is that this report will provide an accessible resource for as wide a cross-section of society as possible. People should feel empowered to build out their own adoption plans and roadmaps, and to test out digital twins in entirely new and untested domains

4. Executive summary

As the UK looks to respond, adapt, and recover from the COVID-19 pandemic, urgent, sustained, and collective action will be needed to reignite different layers of our economy and society. Digital twins have a potentially powerful role in helping us do so. But there is confusion over what a digital twin is, how one can be used, and how one can be commissioned and designed.

This report outlines how digital twins can be adopted effectively to cope with unprecedented levels of risk and uncertainty, and why targeted support for the UK's digital twin ecosystem will unlock value for our people, economy, society, and planet.

The recommendations we highlight would come as part of a broader programme of investment that would also enhance the UK's research, skills, infrastructure, and core engineering capabilities.

Primarily, it seeks to build consensus around the terminology used to define digital twins, recognising that there are a wide variety of competing definitions and misunderstandings emerging across the UK that can cause confusion. In doing so, we build towards a working definition of a digital twin as:

A relevant, virtual representation of the state and behaviour of something physical or non-physical with a functional output in the real-world.

Building on this definition, techUK recommends that decision-makers view a digital twin as a problem-solving approach (rather than an isolated product or service) that is grounded in the systemic integration of different socio-technical components.

Digital twins can be devised with different use cases, technical components, lifecycle stages or levels of complexity in mind, and these are likely to evolve in scope and purpose over time. Taking account of this diversity is important as it helps us to understand how driving interoperability between diverse ecosystems of digital twins can facilitate "systems thinking".

The report outlines a series of recommendations for government and innovation bodies to level up innovation and investment in digital twins and fully exploit the UK's budding expertise in this technology.

The main component of this report, however, is advice to those who are seeking to develop and adopt digital twins. The advice provided is not sector or domain-specific, but sets out general principles and methods that, if followed, can ease the process of digital twin adoption.

To close, the report highlights some of the 'prizes' to be won through the scaled development, adoption, and diffusion of digital twins across the UK. Here, we contend that digital twins are already delivering transformational benefits across the UK, and that the accelerated adoption of digital twins will drive decarbonisation, trigger the reduction of social inequalities, and drive sustainable R&D-led growth.

5. Summary of recommendations

Recommendation 1	Develop a cross-cutting, interdisciplinary coordinating body to drive forward digital twin adoption and diffusion in the UK
Recommendation 2	Scope out barriers and value associated with digital twins via strategic demonstrators
Recommendation 3	Trigger the adoption of digital twins across the UK by exploring the development of an online digital twin procurement portal
Recommendation 4	Identify talent pipeline requirements and anticipate levels of future demand for skills across the UK's digital twin ecosystem
Recommendation 5	Net zero 2050 digital twin demonstrator

Recommendation 1 - Develop a cross-cutting, interdisciplinary coordinating body to drive forward the adoption and diffusion of digital twins in the UK

Core inputs

- 10-year public investment of £150 - £200 million focused on digital twin innovation, adoption, and diffusion (and the take-up of current and near-to market technologies) which would come as part of a broader programme of investment that would also enhance the UK's research, skills, infrastructure and core engineering capabilities
- Coordination from the Department of Business, Energy, and Industrial Strategy (BEIS) and UK Research and Innovation (UKRI)

Core activity

- 10-year public investment to develop a cross-cutting, interdisciplinary coordinating body designed to:
  - Bring diverse stakeholders together with UK industry to support the co-designing of inclusive, sector-level digital twin visions and adoption roadmaps
  - Identify common information requirements and capability gaps (that would need to be addressed by a broader programme of public investment) in the domains of: (i) net zero; (ii) built environment; (iii) public sector and public good; (iv) movement of people and goods, and; (v) productivity, manufacturing, and engineering
  - Incentivise (via tax credits or conditional innovation funding) the formation of multi-party agreements between diverse stakeholders and UK industry
  - Provide guidance on how to develop and implement common codes of conduct (covering minimum expectations around data use, the public functions of digital twins , and risk and uncertainty typologies) via supportive governance frameworks

Output

- A comprehensive, 10-year course of diversified investment that will drive the development, adoption, and diffusion of digital twins across 'mission-critical' domains (as part of a broader programme of investment)

Outcomes

- Increased take-up of digital twins across the UK by a broader range of people (using current and near-to-market technologies)
- Dramatically enhanced levels of collaboration between industry, academia, and Government across the UK's digital twin ecosystem
- Enhanced understanding of common information and capability gaps (associated with the foundational capabilities of a digital twin- 'sensing', 'understanding', 'deciding', and 'acting') that are presently inhibiting the rollout and connecting-up of digital twins in key domains
- Reduction of legal costs associated with developing and using a digital twin
- Enhanced delivery capacity regarding:
  - UK's net zero 2050 objectives
  - The reduction of regional and social inequalities
  - Accelerating R&D-led growth

Recommendation 2 - Demonstrate value from (and explore barriers to) the adoption and diffusion of digital twins via strategic demonstrators

Core inputs

> £1.5- £3 million per demonstrator between 2021 – 2024

i. High-level of ambition = 4-6 demonstrators per domain

ii. Minimum level of ambition = 2-3 demonstrators per domain

> Coordination from UKRI and strategic engagement with techUK's Digital Twin Working Group (DTWG) to scope out feasibility of different demonstrators

Core activity

> Fund a series of strategic demonstrators from 2021-2023 to highlight how value can be derived from digital twins across the following five domains:

iii. Enhancing the UK's global leadership in delivering on net zero 2050 objectives (bringing together the UK's world-leading geospatial community and those focused on building digital twins of the UK's natural environment)

iv. Driving sustainable outcomes across the UK's built environment by supporting the continued development of the CDBB's Information Management Framework [IMF] (which will provide an early blueprint for other domains)

v. Enhancing the day-to-day operational decisions in the management, delivery and observation of public agencies and outsourced social services (emphasis should be placed on integrating digital twins applied to three key areas: social housing, healthcare, and childcare)

vi. Facilitating the safe return of passengers to clean modes of public transport as the UK emerges from the COVID-19 pandemic (building on existing national-level transport and mobility digital twin initiatives)

vii. Accelerating the rollout of 'factory' digital twins and the scaled deployment of smart machines and robotics across the UK's advanced manufacturing sector

Output

> A diversified portfolio of public investment that will enable the UK Government to scope out key areas where further investment and support will be needed

> Demonstration that digital twins (developed from current or near-to-market technologies) can deliver transformational positive externalities in the real-world

Outcomes

> Improved understanding of the information and data required to build and scale digital twins in key application domains

> Improved understanding of the skills and areas of foundational research required in key application domains

> Improved understanding of existing standards and techniques used to integrate data sets and digital twins in key application domains

> Improved understanding of the different analytical requirements required in key application domains

Recommendation 3 - Trigger the adoption of digital twins across the UK by exploring the development of an online digital twin procurement portal

Core inputs (funding and people)

- Public investment: £1 – £1.5 million
- Coordination from BEIS and UKRI
- Strategic collaboration and guidance from techUK's Digital Twin Working Group (DTWG), enabling UKRI to identify procurement barriers

Core activity

- Engage with techUK's DTWG throughout 2021 to understand the existing barriers to digital twin procurement in the UK
- Lay the foundation for public investment in 2022 to develop a dynamic, cross-sector digital twin purchasing platform designed to ease the procurement and integration of digital twins

Output

- A dynamic, cross-sector digital twin purchasing platform that enables generalist decision-makers procure digital twins effectively

Outcomes

- Enhanced visibility and reduced complexity of digital twin offerings emerging across the UK
- Improved affordability and quality of digital twin offerings derived from improved levels of competition between UK suppliers
- Enhanced awareness of the 'through-lifecycle' value of deploying digital twins, and avoidance of short-sighted public investments

Recommendation 4 - Identify talent pipeline requirements and anticipate levels of future demand for skills across the UK's digital twin ecosystem

Core inputs

- Strategic engagement with techUK's Digital Twin Working Group (DTWG)
- In addition, as part of a broader programme of investment CDTs could be put in place to train a new wave of researchers, scientists, and engineers
- Coordination from UKRI

Core activity

- 10-year programme of public investment to identify what a world-leading skills base for digital twin adoption and innovation looks like
- Bring together diverse areas of expertise to train the next generation of engineers and scientists with the skills, knowledge, and confidence they need to tackle barriers associated with the development, adoption, and diffusion of digital twins in the UK
- Develop a strategic partnership with techUK's DTWG to understand industry demand for key skills and competencies

Output

- Assessment of the skills needed to enable adoption and innovation of digital twins (based on current and near-to-market technologies)
- Put in place appropriate mechanisms to deliver the skills that will be needed (with emphasis on skills related to apprenticeships, technicians, software developers/ users)
- Enhanced understanding of industry appetites towards co-investment in CDTs

Outcomes

- Enhanced understanding of relevant capacities, training, and career pathways associated with the UK's digital twin ecosystem
- Enhanced understanding of how digital twins can be used to upskill, and drive collaborative, immersive innovation across the UK in other domains

Recommendation 5 - Net zero 2050 digital twin demonstrator

Core input

- Demonstrator funding of £1.5 - £3million over 2021-2022
- Coordination from UKRI
- Strategic partnership with techUK's Digital Twins Working Group (DTWG)
- Strategic partnership with the Centre for Digital Built Britain (CDBB)

Core activity

- Funding a strategic demonstrator between 2021 – 2022 to demonstrate how digital twins can enhance the UK's global leadership in delivering on net zero 2050 objectives

Output

- A live demonstrator that will enable UK industry, the National Digital Twin Programme, and the UK Government (BEIS, UKRI) to scope out the barriers and opportunities associated with deploying digital twins in order to accelerate decarbonisation

Outcomes

- Demonstrable decarbonisation benefits associated with the deployment of a digital twin (ideally in line with the COP 26 themes: clean energy, clean transport, nature-based solutions, adaptation and resilience, finance)
- Improved understanding of the information and data required to build and scale digital twins in key application domains
- Reinforced industrial and technological capabilities in simulation, modelling, predictive data analytics, cloud, AI and HPC
- Improved understanding of the skills and areas of foundational research required in key application domain
- Improved understanding of existing standards and techniques used to integrate data sets and digital twins in key application domains
- Improved understanding of the different analytical requirements in key application domains

6. Introduction

The increasing complexity and risk associated with making decisions, coupled with the proliferation of digital technologies across the UK's economy and society, has triggered the emergence of a vibrant digital twin ecosystem.

Arising out of the need to leverage information facilitated by digital transformation, many different sectors, organisations and decision-makers are waking up to the notion that digital twins can help to unlock new economic advantage, support the green industrial revolution, and accelerate R&D-led growth.

However, to-date, nebulous definitions and competing terminology have meant that the term 'digital twin' is often seen as a buzzword that frequently creates confusion and uncertainty. This, in turn, has presented a barrier to adoption and stymied the scale-up of the UK's digital twin ecosystem.

Today, those considering the value of digital twins face a lack of clear, targeted advice around how digital twins can be adopted effectively, and why targeted support for the UK's digital twin ecosystem will unlock value for our people, economy, society, and planet.

Notably, this report has been developed via engagement with techUK's interdisciplinary Digital Twins Working Group (DTWG). The analysis we present is intended to drive consensus around:

> The terminology used to describe digital twins

> The principles underpinning digital twin adoption

> The economic, social, and environmental prizes associated with digital twins

> The steps that the UK Government can take to unlock value across the UK's digital twin ecosystem

7. Understanding digital twins

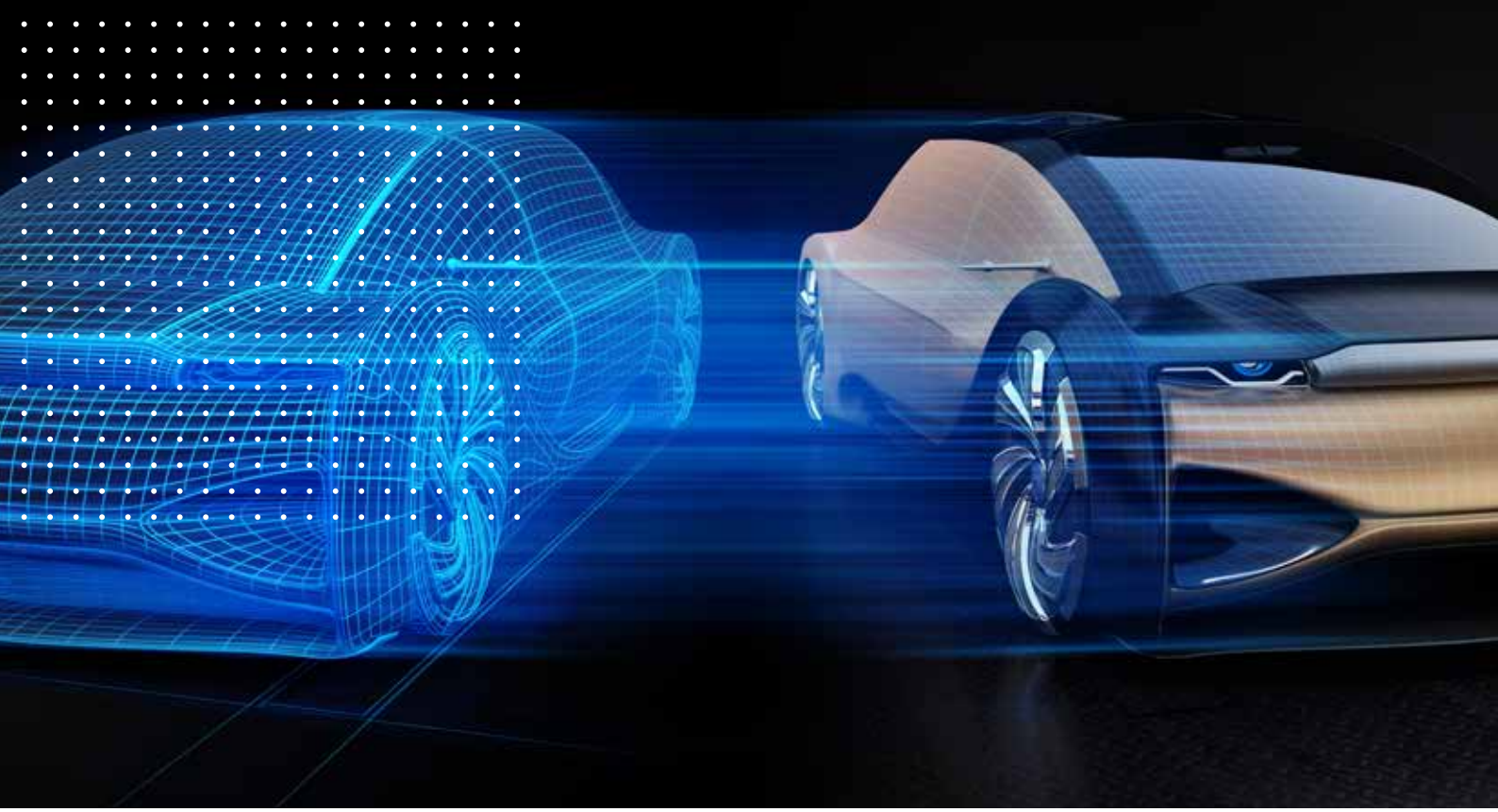
Digital twin evolution

The global market for digital twins – worth £2.7 billion in 2019 – is growing rapidly and projected to reach £34.6 billion in value by 2026.[1] Given the scale and pace of this growth, digital twins are often regarded as new, unproven technologies with no clear historical precedent.

This is misleading. Pioneering companies have been exploring ways to use 'digital twins' to improve their products and processes since the early 2000s.[2] Yet wide-reaching issues of connectivity, computing, data storage, and bandwidth- that enable digital twins to sense, understand, decide, and act- have long proved beyond the reach of the vast majority of organisations across the UK.[3]

However, as the UK undergoes a technological revolution, increased access and falling costs of computational power, sensors, integration tools, data modelling and analytics, and actuators has led the UK to a digital twin adoption 'tipping point'.

Indeed, the concept of developing, adopting, and connecting a digital twin is more feasible now than ever before- presenting a need for consensus building around *what* digital twins are and *how* they work.



What is a digital twin?

Despite the promising trajectory of the UK's digital twin market, there are many competing definitions of the term 'digital twin'. Confusion generally arises as different sectors, stakeholders, and decision-makers have differing views on the overarching purpose of a digital twin.

As a result, existing definitions tend to be conflictual or sector-specific. This limits the capacity of decision-makers to understand the nature and focus of digital twins emerging in other sectors, and the potential of the ecosystem as a whole.

At a fundamental level, however, the term 'digital twin' simply relates to an intrinsic connection between a relevant, virtual representation and something physical (or non-physical) in the real-world.

Crucially, a digital twin is not a standard off-the-shelf solution that can be procured in a linear fashion. Rather, a digital twin represents the culmination of a significant systems integration (SI) effort that yields incremental benefits as it evolves.

With this in mind, techUK defines a digital twin as:

> **A relevant, virtual representation of the state and behaviour of something physical or non-physical with a functional output in the real-world**

Notably, this definition is intended to be durable and transportable across a wide range of different sectors and is grounded in input from techUK's interdisciplinary Digital Twins Working Group (DTWG), which brings together decision-makers from areas such as aerospace, construction, cyber security, data analytics, defence, energy, financial services, law, transport, social care, telecommunications and beyond.

How does a digital twin work?

Armed with this definition, it can still be difficult to comprehend how digital twins work. As such, it is useful to consider Figure 1, which clearly visualises how different foundational capabilities come together to make up a digital twin.

Building on Figure 1, a useful starting point when describing how a digital twin works is to understand what the intended 'outcome' a digital twin is. In short, what is the relevance of building and deploying a digital twin? In turn, it is also useful to understand that a digital twin involves 'sensing' outcomes (i.e. creating signals that capture operational and environmental information pertaining to the real world).

Sensing capabilities provide a backbone for the application of data models and analytics, which enable enhanced 'understanding' of the state and behaviour of the real-world and empower people to 'decide' on what they want to do next.

With a clear decision in mind, a digital twin then involves 'acting' in the real world- as these actions manifest in the real-world, the twin senses variance in outcomes, feeding back into the digital twin itself. This is a critical element to understand as isolated simulations are often misunderstood as digital twins, even when they lack a continuous link to the real-world. Finally, digital twins also relate to 'constellations of twins'. By this, we mean that digital twins can be connected, talk to and learn from each other- something more commonly referred to as interoperability.

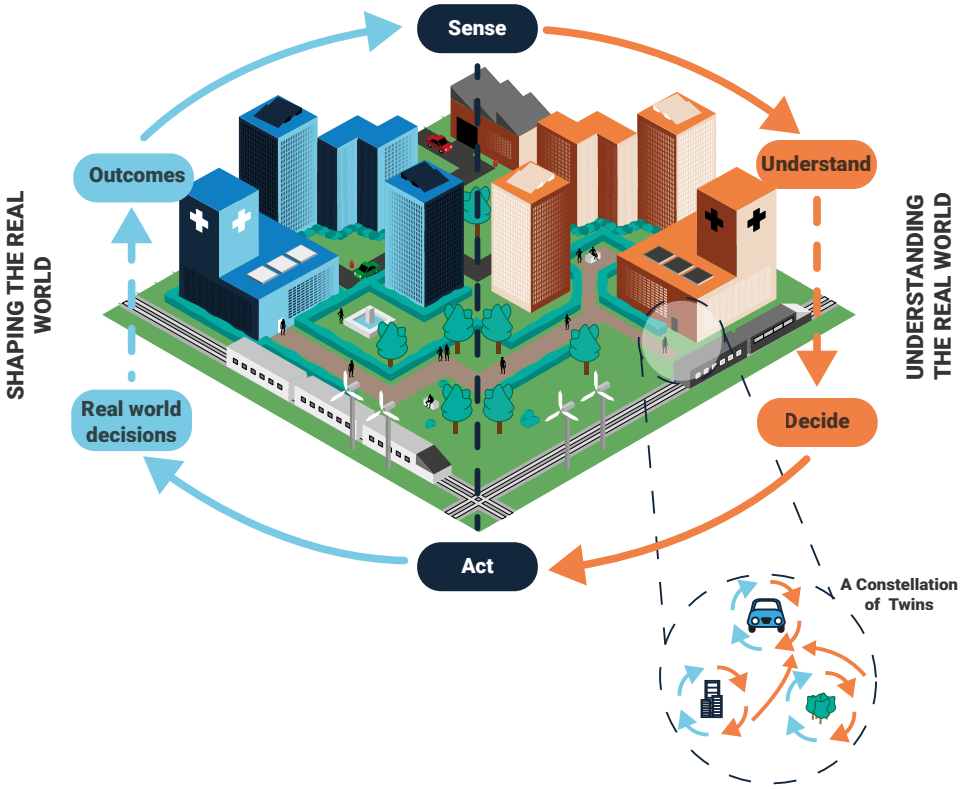


Figure 1: Digital twin concept

What technologies are involved in a digital twin?

Digital twins can be differentiated based on their diverse technical architectures. However, it is worth noting that there is no definitive set of technologies that a digital twin must comprise of. Instead, there are foundational relationships between different components that must be considered (see Figure 2).

A straightforward outline of the categories of technical capabilities that provide a foundational environment for digital twin adoption can be found below:[4]

- **Sensors:** Sensors distributed throughout a process or to monitor assets create signals that enable the twin to capture operational and environmental data pertaining to the real world.
- **Data:** Real-world operational and environmental data from the sensors are *aggregated* and combined with other relevant data.
- **Integration:** Sensors communicate the data to the digital world through integration technology (which includes edge, communication interfaces, and security) between the physical world and the digital world, and vice versa.
- **Models and analytics:** Techniques are used to model and analyse the data through algorithmic simulations and visualisation routines are used by the digital twin to produce insights.
- **Actuators:** Should an action be warranted in the real world, the digital twin produces the action either by way of actuators or via human intervention, which trigger, alter or inform the physical process.

Useful technical components, systems, data, and infrastructures can already exist within an organisation that is looking to build a digital twin. In these instances, technical capabilities can be extended or re-purposed to support digital twin development and deployment. Where there are gaps, new solutions must be procured.

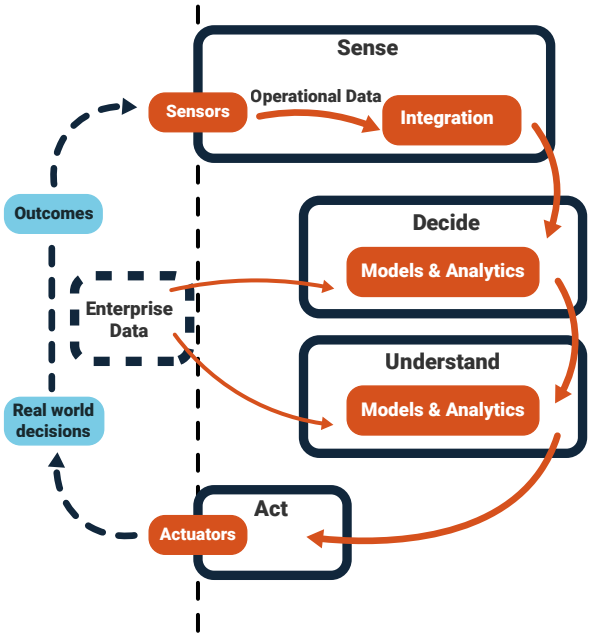


Figure 2: Digital twin conceptual architecture

Technical capability assessment

Faced with a wide variety of different technical components involved in the development of a digital twin, it is useful to incorporate an objective framework (grounded in common language) that enables different stakeholders, innovators, and potential collaborators to understand what the digital twin can do, and what it can become. In this regard, the Connected Places Catapult (CPC) has recently published a useful multi-criteria assessment framework that can be used to evaluate digital twin initiatives of all shapes and sizes (see Figure 3).[5]

Notably, this framework has been developed with CPC's aims and objectives in mind. Different digital twin adopters may find it useful to adjust the weighting of criteria (and potentially scoring thresholds) to reflect the nuances of their own unique strategy and mission. For instance, factors like the extensibility or accuracy of a digital twin may also be valuable to include.

Criterion	Description
Data exchange	Does it have the ability to ingest real-time data to enable the use case to be tested in real-time?
Scalable	Is it scalable over a wider geographic catchment?
Functionality upgrade	Can functionality be augmened over time?
Multiple Scenarios Run	Can it optimise multiple senarios?
Multiple use case	Can it support evaluation of multiple use cases?
Prototype	Is it easy to prototype and incrementally develop through TRL's?

Figure 3: Technical review framework

What is the 'use case' of a digital twin?

Beyond these technical characterisations, one of the most critical differentiators of a digital twin relates to the 'use case' - *how* and *why* a digital twin is being deployed.

Incorporating a clear framework to capture relevant use cases is an essential (yet often overlooked) consideration because digital twins cover a broad range of applications and may evolve in scope and purpose over time.

In Figure 4, we present an easily digestible framework that highlights three core categories of digital twin use case that are useful to keep in mind.

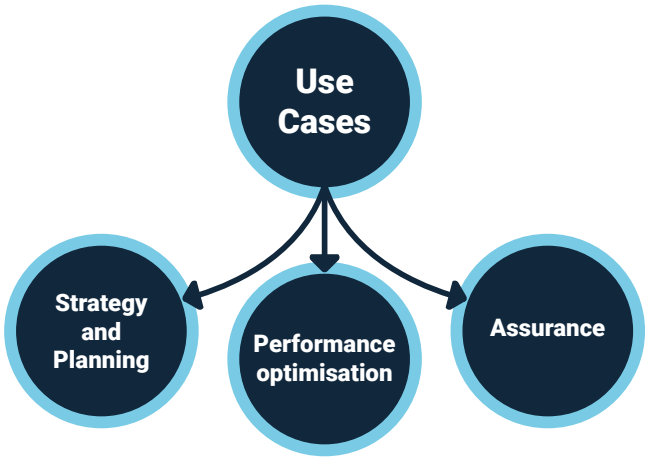


Figure 4: Digital twin use case framework

Strategy and planning

The first use case category relates to 'strategy and planning'. This is a rich, expanding category of digital twins concerned with exploring the effects of policy, strategy, and planning.

Notably, strategy and planning digital twins help users to expose gaps between plans, actions, and outcomes, and support multi-criteria decision-making by enabling users to test and model various trade-offs and options.

Leveraged effectively, strategy and planning digital twins can also expose a wide range of feasible interventions and decision-pathways, supporting collaborative action and resilience building.

Emerging applications of strategy and planning digital twins often focus on multi-criteria analysis of policy decisions and interventions[6], prototyping[7], and analysing systems-level interdependencies for master planning.[8]

For example, the Destination Earth (DestinE) initiative aims to develop a very high precision digital model of the Earth to monitor and simulate natural and human activity, enabling users to develop and test scenarios that support the evaluation of European environmental policies.[9]

Performance optimisation

Another digital twin use case category focuses on **'performance optimisation'**. This is a fast-growing, high potential area of development set to dramatically improve the performance, availability, and safety of real-world systems.

Performance optimisation digital twins highlight patterns of use and degradation over time, support predictive maintenance, repair, and overhaul. They are also extremely useful in supporting capital versus operating expenditure decisions, in balancing cost with expected levels of return, and in supporting digital rehearsals under conditions of deep uncertainty and risk.

Today, most digital twin offerings fall under this use case, with notable applications in areas such as vaccine manufacturing[10], supply-chain optimisation[11], low carbon energy production[12], and waste electrical and electronic equipment recycling.[13]

Assurance

A third digital twin use case category relates to enhancing levels of **'assurance'** in the safety or resilience of real-world twins, supporting the prevention of errors and mistakes. Assurance digital twins are particularly relevant in safety critical domains, where erroneous decision-making can have grave, cascading effects.

This digital twin use case category can also be leveraged to certify levels of safety or resilience for products, services, and features, or help to extend the life of high value assets that are used in critical applications. During periods of rapid technological, social, or environmental change, they provide decision-makers with a body of reliable metrics, supporting decision-making under deep levels of uncertainty and risk.

Interesting examples of assurance digital twins focus on extending the life of high value assets, enhancing safety in hazardous domains[14], and supporting risk assessment.[15]

Prioritising digital twin 'use cases'

In reality, most organisations will have multiple potential use cases for digital twins- some of which are more important, urgent, or feasible than others. Thus, it is important to prioritise the use case to focus on, otherwise there may be room for doubt that the proposed investment is the best use of capital.

The need to prioritise the use case is even more pronounced for a digital twin (or a constellation of digital twins) that represents a whole system, where the needs of multiple stakeholders must be balanced.

Again, the prioritisation of use cases requires an assessment framework that considers a range of metrics. One such framework was recently published by the Connected Places Catapult (CPC), which includes twelve broadly relevant criteria (see Figure 5).[16]

Criterion	Description
Decision support times	Will the use case demontrate the ability to support decision makinig within operational time-lines?
Efficiency	Will use case demonstrate viability/efficency gains in existing processes/operations?
Data availability	Whether the relevant data exists or to enable the test case
Strategic Alignment	Does the use case align with key imperatives: levelling up, net-zero or post-COVID recovery
Self-sustaining	Is the use case profit-making or at least self-sustaining?
Synergies	Is the use case synergistic with other use cases on the longlist?
Users	Will the use case benefit may users? i.e. multiple organisations / departments
Direct Benefits	Does the use case offer visible and drect benefits to citizens or businesses?
Private investments	Is there evidence of private sector investment in the use case?
Innovation	To asses he degree of originality embedded within the proposed use case
Global market	Projected global market size near 2030
UK competitive strength	Is there a country that is a clear international forerunner?

Figure 5: Use case assessment framework

The CPC's framework is useful and provides an objective and transparent way of prioritising digital twin use cases based on how they generate impact. It is worth noting, however, that the notion of generating impact is value-laden (i.e. success is dependent on the relative aims and aspirations of the sector, organisation or individual in-question). Ultimately, therefore, the most successful digital twin initiatives will be grounded in bespoke analysis of the decision-making context at hand and a dynamic, human-centred understanding of what success looks like.

Complexity

With our core definition and use case framework in mind, it is worth noting that digital twins can be characterised based on their degree of 'complexity' (i.e. the number of variables, interdependencies, and interactions that must be represented by a digital twin).

While a digital twin does not need to address all possible levels of complexity, the messier, more difficult a situation is, the harder it is likely to be to tame through the application of a digital twin.

For example, in commercial aerospace, it may be significantly easier to develop a useful digital twin of one isolated airplane **'component'** (such as a turbine blade or jet engine compressor), relative to the complexity of optimising the performance of a key **'process'** (such as the predictive maintenance or refueling of an airplane) or of developing strategic plans for the UK's entire aerospace **'system'**.

Notably, the real value comes when digital twins of differing levels of complexity are rolled into one (or more likely, a constellation of digital twins). By driving interoperability of this kind, digital twin users can effectively zoom into specific components while benefits percolate all the way through to the systems-of-systems level.

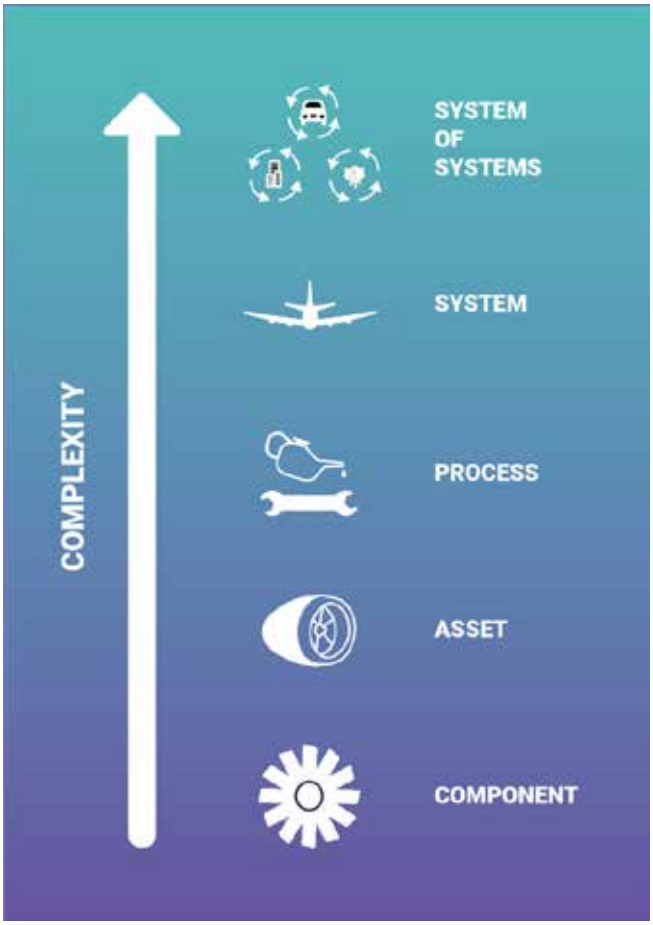


Figure 6: Complexity spectrum

Lifecycle integration

Finally, while a digital twin does not strictly have to survive the full lifecycle of something in the real-world, the value of a digital twin is likely to increase the more lifecycle stages it supports.

Indeed, digital twins are most effective when they look forward, beyond decisions and interventions that are made today or tomorrow. In practicality, this means recognising that digital twins can be applied at different lifecycle stages, and that there is value in driving interoperability between these different digital twins.

By joining digital twins of different lifecycle stages up, captured data adds value for longer and helps to drive through-life financial advantages and operational benefits.

As such, it is important not to treat digital twins in isolation and to recognise that enhancing strengthening connections between digital twins at different lifecycle stages is critical to delivering return on investment.

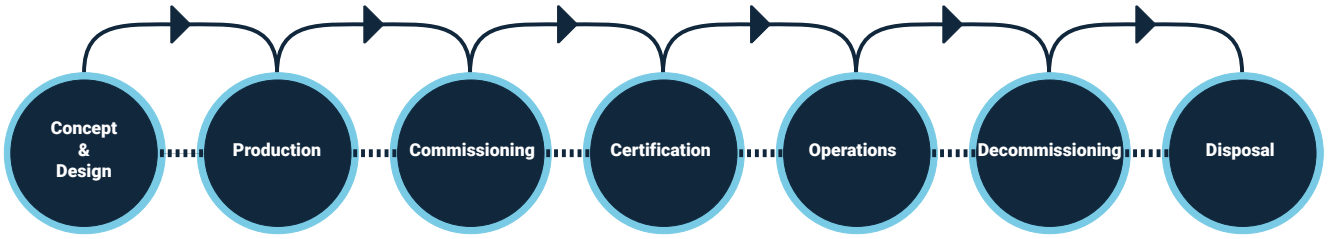


Figure 7: Lifecycle integration

Conclusions

- techUK defines a digital twin as a relevant, virtual representation of the state and behaviour of something physical or non-physical with a functional output in the real-world.
- A digital twin has five foundational technical components (sensors, data, integration, analytics, actuators) which can be collectively assessed through the adoption of a multi-criteria assessment framework.
- Understanding which 'use case' category a digital twin relates to is key and employing a robust, multi-criteria assessment framework enables the prioritisation of use cases.
- Digital twins can be devised at different levels of complexity, with the real value often occurring when digital twins are connected.
- A digital twin can integrate with its real-world at any point in their lifecycle, and connecting digital twins can support the balancing of short-term and long-term value extraction.

Recommendation: Trigger the adoption of digital twins across the UK by exploring the development of an online digital twin procurement portal

Core inputs (funding and people)

- Public investment: £1 – £1.5 million
- Coordination from BEIS and UKRI
- Strategic collaboration and guidance from techUK's Digital Twin Working Group (DTWG), enabling UKRI to identify procurement barriers

Core activity

- Engage with techUK's DTWG throughout 2021 to understand the existing barriers to digital twin procurement in the UK
- Lay the foundation for public investment in 2022 to develop a dynamic, cross-sector digital twin purchasing platform designed to ease the procurement and integration of digital twins

Output

- A dynamic, cross-sector digital twin purchasing platform that enables generalist decision-makers procure digital twins effectively

Outcomes

- Enhanced visibility and reduced complexity of digital twin offerings emerging across the UK
- Improved affordability and quality of digital twin offerings derived from improved levels of competition between UK suppliers
- Enhanced awareness of the 'through-lifecycle' value of deploying digital twins, and avoidance of short-sighted public investments

8. Early digital twin adoption planning

Innovators across the UK are constantly coming up with brilliant new ideas for digital twin initiatives. Often, they feel energized, inspired, and ready to forge ahead. Yet one of the first challenges they face is building an effective adoption plan.

Writing an early adoption plan for a digital twin venture is beneficial in a variety of ways, including gaining buy-in and generating enthusiasm for an idea. A clear adoption plan will also dramatically improve the odds of successfully developing and integrating a digital twin, raising capital, and sustaining support.

Whether the intention is to build a new digital twin from scratch, expand an existing initiative, or collaborate with an established organisation, taking the time to build an adoption plan for a digital twin initiative will provide an opportunity to thoroughly evaluate the idea. It is also a way for stakeholders – namely, investors, managers, and the people who control vital resources that you need to initiate a digital twin – to assess the feasibility of the concept.

In this chapter, we put forward a set of general principles and methodologies that, if followed, can ease the process of digital twin adoption. The long-term goal of this process is to build towards an adoption 'roadmap' that helps to navigate the opportunities and inevitable barriers that will be faced and, perhaps most importantly, to develop strategies to avoid problems before they arise.

When crafting a digital twin business plan for the first time, there may be a temptation to devote too much effort to detailed, month-by-month projections that outline exactly how the digital twin will evolve.

However, savvy technologists and investors understand the difficulty of building plans with a high level of granularity-especially under conditions of deep uncertainty and risk. As such, organising initial planning around four foundational elements is useful for striking a balance between generating near-term value and developing the capacity to extract value long-term.

People and skills

One important factor to keep in mind during the early stages of a digital twin initiative is the **skills** and **people** required to develop, maintain, and operate a digital twin, as well as any outside parties that will provide important resources.

There are many different potential players at different times, so it is worth dedicating time to understanding whether you need to upskill, bring in new people, or if you can leverage existing talent. That said, there is no definitive set of skills that a digital twin initiative must rely on.

On the one hand, triggering digital twin adoption requires individuals that have **extensive domain expertise.** This is particularly important where the subject matter is highly complex (e.g., in areas such as pharmaceuticals or advanced manufacturing) because the core goal of a digital twin is to enhance understanding of the state and behaviour of the real-world system. If your team lacks an understanding of how the real world behaves to begin with, this can present immediate barriers to adoption.

On the other hand, there is a need to recruit talented individuals that are comfortable with **interdisciplinary methodologies and research.** This is important because digital twins result from significant systems integration (SI) efforts, whereby multiple sources of information and components are brought together. Without an interdisciplinary ethos at the core of your team, you will find it difficult to understand where benefits can be derived and where risks may emerge.

Additionally, given the potentially transformative role that digital twins can play across multiple layers of the UK's economy and society, it is vital to **champion diversity** (relating to gender, ethnicity, LGBT+, disability, neurodiversity, and social mobility). More often than not, looking beyond the scope of conventional 'specialists' will help to ensure that a digital twin initiative is human-centred and sustainable and play a critical part in delivering positive externalities across the UK.

Finally, the capacity of individuals to think in '4D' is crucial. By this we mean recruiting individuals that can **think in abstract terms, over time.** This is a particularly important trait to look for when building an effective team because digital twins are flexible and dynamic and will likely evolve in scope and purpose as time goes on- requiring individuals that can think ahead in order to 'future-proof' complex conceptual architectures.

Opportunity

During the early stages of digital twin adoption, it is also vital to consider the **opportunity** presented by adopting a digital twin approach. Here, we mean what the digital twin will do and for whom, how it will grow and how quickly, what its economics are, and what might stand in the way of success.

Dedicating time to understanding the opportunity presented by a digital twin should not be a one-off, linear exercise. On the contrary, there is a need to look beyond the immediate opportunities and recognise that there are evolving ideas of what success really means.

If proponents only consider the immediate opportunities now, the through-lifecycle value of a digital twin initiative may not be captured. Likewise, as appetites for different levels of decision-making evolve, there may be a requirement to adapt the use case of a digital twin.

Context

Building on the above, opportunities exist in a **context.** By this, we mean that there are many factors (such as interest rates, regulations, or industry standards) that will inevitably change but that cannot be directly controlled.

While they cannot be controlled, these contextual factors can have a direct bearing on the feasibility of a digital twin and a tremendous impact on nearly every aspect of the entrepreneurial process.

In this light, early adoption plans should prioritise the need to understand context. In practicality this means:

1. **Developing a heightened awareness of the digital twin's context, and how it helps or hinders the proposal in-question**
2. **Demonstrating understanding that this context will inevitably change and describe how those changes might affect the use case of a digital twin**
3. **Spelling out what can (and will) be done if the context grows unfavorable**
4. **Explain what (if anything) can be done to affect context in a positive way (e.g. is there scope to have an impact on regulation or industry standards through lobbying efforts?)**

By addressing these areas, digital twin proponents can build a strong foundation for digital twin adoption and embed practices that will prove valuable across the lifecycle of the digital twin itself.

Risk and reward

When starting out, it is also important to build up understanding of the **risk and reward** associated with your digital twin.

This means that an initial business plan should directly confront the factors that might go wrong – in terms of people, opportunity, and context – and propose a set of dynamic, adaptive responses.

For example, what happens if one of the new venture's core domain experts leaves? What happens if supply chain disruption makes it difficult to acquire and integrate technical capabilities required for your digital twin in a timely fashion?

These are undoubtedly hard questions, especially during the early phases of an initiative – yet those who do pose them and seek to provide clear answers will stand in good stead as they look to form early digital twin adoption roadmaps.

Conclusions

- Early adoption planning is important in gaining buy-in, generating enthusiasm for an idea, and will dramatically the improve odds of success when it comes to raising capital, and sustaining support.
- There is no definitive set of skills that a digital twin initiative must rely on, but effective teams will blend domain expertise, interdisciplinary working environments, and involve diverse individuals that have the capacity to think in 4D over time.
- When considering the opportunity associated with a digital twin, there is a need to look beyond the immediate opportunities and recognise that there are evolving ideas of what success really means.
- It is vital to address factors (such as interest rates, regulations, or industry standards) that will inevitably change but that cannot be directly controlled.
- Early adoption plans will include a clear, dynamic and responsive approach to responding to anticipated risks and deep uncertainty.

Recommendation: Identify talent pipeline requirements and anticipate levels of future demand for skills across the UK's digital twin ecosystem

Core inputs (funding and people)

- Strategic engagement with techUK's Digital Twin Working Group (DTWG)
- In addition, as part of a broader programme of investment CDTs could be put in place to train a new wave of researchers, scientists, and engineers
- Coordination from UKRI

Core activity

- 10-year programme of public investment to identify what a world-leading skills base for digital twin adoption and innovation looks like
- Bring together diverse areas of expertise to train the next generation of engineers and scientists with the skills, knowledge, and confidence they need to tackle barriers associated with the development, adoption, and diffusion of digital twins in the UK
- Develop a strategic partnership with techUK's DTWG to understand industry demand for key skills and competencies

Output

- Assessment of the skills needed to enable adoption and innovation of digital twins (based on current and near-to-market technologies)
- Put in place appropriate mechanisms to deliver the skills that will be needed (with emphasis on skills related to apprenticeships, technicians, software developers/ users)
- Enhanced understanding of industry appetites towards co-investment in CDTs

Outcomes

- Enhanced understanding of relevant capacities, training, and career pathways associated with the UK's digital twin ecosystem
- Enhanced understanding of how digital twins can be used to upskill, and drive collaborative, immersive innovation across the UK in other domains

9. Early digital twin adoption roadmap

Once an initial, foundational business plan for your digital twin has been developed, the next stage involves building this broad plan into a more detailed adoption roadmap.

While there is no perfect model to use in this regard, again there are fundamental dimensions that should be taken into consideration. These relate to:

1. **Setting direction**
2. **Legal guidance**
3. **Defining information requirements**
4. **Defining levels of fidelity and update frequency**
5. **Baking-in security**
6. **Developing foundations for interoperability**

While we have outlined a linear process above, it is worth noting that digital twin adoption is, in practice, flexible and non-linear. Indeed, different groups within a team executing a digital twin adoption roadmap may conduct more than one stage concurrently, or across the full lifecycle of the initiative.

Setting direction

Digital twin adoption requires attention to people, processes and technology with a user led focus on solving business problems. This means that it is vital to employ methodologies that enable you to empathise with people and the business context, to define the problem that you are setting out to solve and, ultimately, set direction. These are critical activities, yet infrequently supported by protocol or rigour.

Empathise

When setting direction, it is critical to observe, engage and **empathise** with people to understand the experiences and motivations driving demand for a digital twin. This is particularly important as digital twins cut across siloes and traditional organisational boundaries. It is also crucial to immerse yourself in the real world so that you can gain a deep understanding of the issues involved in adopting a digital twin approach.

Depending on the constraints, a substantial amount of information should be gathered at this stage. This will inform the next steps and develop the best possible understanding of people, their needs, and the outcomes-focus that is driving forward digital twin adoption.

There are a wide array of 'visioning' techniques that can be employed to build up a rich picture of future aspirations and expectations surrounding the digital twin in-question. For example, employing 'Postcards from the Future' can enhance clarity about aspired directions of change to pursue and clarify assumptions about the way in which the future is expected to unfold.[17] This is a line of investigation that can also be supported by the adoption of 'Design Thinking'.[18]

Additionally, employing methods such as 'Analytical Aspiration Mapping' can be useful as a means of exploring relationships between specific goals, to identify programme synergies, priorities and, critically, to isolate areas in need of further exploration.[19]

Given the uncertainty of the final scope of the digital twin, it is vital to incorporate these kinds of agile methods when building an adoption roadmap. Doing so will drive the identification of opportunities that have not previously been considered, enable the avoidance of inefficient resource allocation, and provide those in charge of designing, implementing, and using a digital twin with a strong sense of project risks.

Defining the problem

When building an effective digital twin adoption roadmap, it is also important to **define the problem** at the heart of the digital twin journey. This will involve analysing your observations to-date and translating them into a clear, overarching problem statement that can be articulated in a human-centred manner.

Again, there are useful methods that can be used to this end, which drive understanding of problems faced by individuals and organisations, and which lead towards human-centred goals and objectives.[20]

For example, 'Goal Mapping' is a unique, multipurpose analytical tool that can be used to clearly articulate what the challenge or problem looks like. Similarly, sketching out 'Causal Loop Diagrams' can be extremely useful as a means of identifying multiple goals and, crucially, relationships between goals.

Incorporating this kind of method from the outset of a digital twin initiative will drive agreement on where to focus resource, building towards a dynamic, inclusive definition of what a success looks like.

Additionally, when defining the problem, there are a wide range of user research methods that can drive understanding of the needs and motivations of digital twin end users. These methodologies can help in refining the scope of your problem statement.[21]

For example, the use of 'Contextual Inquiries' can provide insights on how different stakeholders and end users perform tasks and duties. Moreover, a technique known as 'User Journeys' can be used to map out possible interactions (known as 'touchpoints') between digital twins and end users- driving the identification of key digital twin design requirements.

Long-term, employing these kinds of methods will help to drive consensus around user needs, enhance digital twin design, put issues into perspective, and uncover new problems before they arise.

Legal guidance

Many potential parties and individuals can be involved in the adoption of a digital twin. This means that the process of legally protecting your digital twin can quickly turn into a (highly costly) contractual 'spider web'.

This issue is compounded when we consider that the purpose of a digital twin may evolve over time. As such, any effective digital twin adoption roadmap will need to consider a wide range of different legal factors, such as:

1. **Responsibility:** What are the main activities, roles and responsibilities and have these been allocated? For example, responsibility for checking and updating content and data, responsibility for storage, back-ups and security, and each parties' roles in setting up and inputting to the digital twin, and for how long.

2. **Liability:** Make a list of what could realistically go wrong – has all the potential liability been allocated? For example, liability for consequences of errors in the data, corruption of the data and/or gaps in the data within the digital twin; liability for accidental or wrongful sharing of data or the digital twin.

3. **IP Rights/Copyright:** Who owns the data within the digital twin, and the digital twin itself? Do other parties have sufficient rights or licences to use the data, and when should these rights cease? For example, should the project team's rights cease on project completion but the client's rights to all data continue in perpetuity?

4. **Data Restrictions:** Will there be any personal data stored/potentially contained within the digital twin and connected data, and what data laws need to be complied with? Does the client or other parties have any restrictions or requirements on data location which limits where the digital twin and data can be stored, e.g. are there requirements for data to remain within a certain jurisdiction?

5. **Technical Specifications:** Have appropriate minimum hardware and software requirements been specified to ensure all parties can participate without delay throughout the process? This includes considering obligations to update software, and use updated versions of software to avoid interoperability problems of parties using different software versions. Are there requirements for parties to maintain the necessary cloud platform or other appropriate licences to access the selected data storage platform?

Acknowledging the various legal factors that must be taken into consideration is one step. The next involves developing an agile, ethical approach to legally protecting your digital twin that minimises costs, but maximises opportunities for dynamic innovation.

Today, there is strong demand for legal arrangements that enable low-cost agile contracting, for the provision of codes of conduct around minimum requirements for data use and digital twin integration (especially at sectoral levels), and a growing need for clear governance frameworks that enable different sectors, stakeholders, and decision-makers to work together to develop and use digital twins at scale.

Defining information requirements

Another important element to note during the early stages of digital twin adoption relates to the need to determine the minimum level of information that you require. When doing so, it is important to maximise alignment with Enterprise Architecture (EA) in-question, and to ensure that digital twin adoption fits in with relevant, overarching information strategies. In short, a digital twin should not be regarded as a toy on the side, but rather a core component of the enterprise decision-making process. Notably, there is an important differentiation to consider here– between what you require to get started, and everything you could possibly know.

Having identified a use case for your digital twin (see Chapter 1), it is vital to establish and categorise 'Organisational Information Requirements' (OIRs).[22] In practicality, this means understanding the minimum level of information that can be used to support strategic decision-making. It is worth keeping in mind that 'organisations' can vary dramatically in complexity and scope. Different decision-makers within and between organisations are also likely to have different needs for information, and there may be a wide cross-section of individuals that need to be engaged to comprehensively determine a useful set of OIRs.

Additionally, it is critical to identify 'Asset Information Requirements' (AIRs).[23] Typically, this means defining the minimum level of information needed for the operation and management of the real-world twin and digital twin. This should also include non-functional data requirements such as how accurate up to date (or fresh), complete, trusted the data needs to be. When initially summarising AIRs, it may suffice to draft-up some simple text outlining which activities are required for operation and maintenance. However, over time, this should be developed into a clear plan of deliverables, with specific methods and procedures identified. Notably, building a comprehensive set of AIRs is a task of scale that should not be underestimated.

Thirdly, it is important to pre-determine a set of 'Plain Language Questions' (PLQs) that can be posed by the client or organisation at different stages in the lifecycle of a digital twin.[24] Simply put, PLQs are requests for information that can be expressed in straightforward, easy-to-understand terms. These PLQs should be designed to inform key decisions and, ultimately, allow those in charge of critical resources to decide whether to proceed to the next phase of digital twin adoption.

Finally, understanding and documenting metadata is crucial.[25] As well as providing the ability to search it is crucial to ensure that all the different factors contributing to a digital twin have a consistent view of the data and its meaning.

Defining levels of fidelity and update frequency

When building out a digital twin adoption roadmap, there is also a need to be clear on the degree of **'fidelity'** desired of the final output of the digital twin.

Notably, the level of fidelity depends on how important the decision is. At a more granular level, fidelity is determined by the number of parameters, their accuracy, and the level of abstraction that will be transferred between digital and real-world twins. Generally, the level of fidelity associated with a digital twin, can be charted on a scale from abstract (low) to extremely precise (high).

When building a digital twin adoption roadmap, it is important to remember that the optimal level of fidelity may change as the use cases of a digital twin evolve over time.

At the time of writing, existing literature is yet to present an exhaustive, high-fidelity digital twin (where parameters for every aspect of the physical twin are captured). The practical reality is that building a high fidelity digital twin is fraught with many challenges and capability gaps, such as low network speeds or insufficient levels of computational power.

If the UK is to develop a globally leading digital twin ecosystem then these capability gaps must be addressed through a broad programme of public and private investment aimed at boosting the accessibility of necessary research, skills, infrastructure, and core engineering capabilities.

In the near-term, however, those developing adoption plans will be best served by determining the minimum level of fidelity that can be attained in order to maximise benefit while minimising expense and technical difficulty.[26]

In a similar vein, it is critical to consider the desirable **'update frequency'** of a digital twin. Put simply, the degree of update frequency you will require will depend on how often you want to take a decision.

More specifically, this means how often models will be updated (i.e. from weekly to real-time or event driven).[27] Again, it is crucial to determine an appropriate and realistic timescale for capturing, analysing and converting data to support real-world decision-making. Not all digital twins require a high update frequency, or real-time connection to function effectively- this will depend on the end-user's intentions.

Instead, those managing early digital twin adoption roadmaps should base the level of update frequency they aim for on the overarching use case. This will help to highlight the minimum amount of information that can support decision-making and reflect changes in the state of the real-world twin over time.

Moreover, having levels of fidelity and update frequency that are good enough but not available in the right timescales would also restrict value. As such it may also be worth considering the significance of latency at this stage of the process.[28]

Baking-in security

If you are adopting and deploying a digital twin, baking-in security from the outset must be a key consideration.[29] Moreover, it is vital to employ a dynamic, adaptive, and resilient approach to security that enables your organisation to proactively respond to emerging cyber risks.

A failure to secure your digital twin, the system in which it is implemented, and the real-world twin could result in potentially catastrophic consequences, such as loss of intellectual property and data, loss of control, and potentially huge costs resulting from down-time, faulty outputs, or data being held to ransom.[30]

It is essential to ensure that digital twin adoption occurs in tandem with a systematic cyber security strategy. While there is no definitive list of security measures that you should incorporate into this strategy, there are four security fundamentals that you must have covered from the early stages of adoption, right through to the end of the digital twin's useful life.

Primarily, there is a need to **implement data security and cybersecurity.** In practicality this means that data used for by the digital twin (both in transit and at rest) should be connected to robust governance practices, and methods of authentication and encryption.

Secondly, there is a need to embed practices that **enhance the dependability and resilience** of your digital twin- defined as 'the persistence of service delivery that can justifiably be trusted, when facing changes'. In basic terms, this means developing and maintaining the mechanisms of fault prevention, tolerance, removal, and forecasting so that you can be sure of consistent, reliable outputs that you can trust. This is particularly important in safety-critical domains, where there is a need to ensure high degrees of accountability and auditability.

Thirdly, **information privacy** is core to the ethical digital twin adoption, given the large amount of data collection and processing involved. In this vein, it is important to ensure that digital twin adoption adheres to existing privacy regulations (such as the EU's GDPR)[31] and, even if data is not personally identifiable, that the benefits of using methods such as masking, redaction, differential privacy, encryption, and lifecycle management are considered early-on.

Finally, there is a need to ensure the physical safety of the digital twin. Safety may sound basic, but it is a key part of protecting a digital twin and those in the real-world. Indeed, when confronting cyber risks there is an enduring need to get 'physical'- this means locking doors to data centres, protecting IT equipment from theft or damage, or preventing computers and servers from overheating. The physical aspects of data storage should also be considered. How much will there be? How fast do you need to access it? Never underestimate the fundamentals.

Developing foundations for interoperability

As the information age gathers pace, future-proofed digital twin adoption roadmaps will prioritise the ability to author, exchange, assure, and subsequently use and re-use data and different modular components.[32] This characteristic, known as 'interoperability', can dramatically enhance the value of your digital twin.

If the UK is serious about developing a world-leading digital twin ecosystem then there must be a clear strategy in place which outlines what blend of approaches to developing interoperability between digital twins serves our national ambition and the interests of our people, economy, society, and planet.

When building an effective digital twin adoption roadmap, it is worthwhile to take stock of existing methods that can be used to enhance interoperability, and to prepare to refactor, if necessary, to commonly accepted frameworks for interoperability.

However, driving interoperability between different data sets and digital twins has proved extremely difficult in the past. While there is broad recognition that interoperability is a desirable characteristic of a digital twin, many obstacles (related to incompatibilities between different data types, technical standards, and analytical capabilities) have proved difficult to overcome at a small scale, let alone across sectoral or disciplinary boundaries.

As a result, numerous 'bottom-up' approaches are emerging around the world which aim to drive consistency in vocabulary, architecture, security, and, ultimately, interoperability between ecosystems of digital twins. For instance, the **membership-based** Digital Twin Consortium has emerged in the US, where the aim is to set de facto technical guidelines and taxonomies, to publish reference frameworks, develop requirements for new industry standards and share use cases.[33]

Such models may prove useful for the early pioneers of digital twins, and for those who have little fear of failing when exploring new areas. However, as the UK's digital twin ecosystem matures- and we gradually gain an understanding of the obstacles and value associated with driving interoperability between digital twins- those building digital twin adoption roadmaps should also consider the availability of solutions that can be leveraged to overcome project-specific barriers to interoperability (and how these align with the UK's national ambition).

In the UK, for example, some forward-looking organisations are already using meta **data sharing** and **semantic modelling** to identify touchpoints for interoperability between digital twins.

techUK member Iotics, for instance, is currently developing groundbreaking tools that overlay data with descriptive metadata to give it meaning that other machines can understand.[34] Similarly, IBM have developed a groundbreaking Digital Twin Exchange.[35] The incorporation of these kinds of approaches are particularly useful in the absence of commonly adopted standards for digital twin interoperability, and are set to be important drivers of organic, industry-led digital twin integration.

It is also vital that the UK takes note of initiatives emerging at a European level and has a clear plan of action aligned with our national ambition. For example, the Destination Earth (DestinE) initiative is shining a light on how a federated cloud-based modelling and simulation platform can be leveraged to integrate digital twins, enable collaborative application development and the integration of users' own data.[36] This is a more top-down approach designed to serve public authorities which is set to spur collaboration between scientists and enable the benchmarking of models and data.

As these approaches are used over time, it will become increasingly clear that a high degree of interoperability between digital twins is both possible and valuable. This will strengthen the case for a commonly accepted frameworks for data sharing and digital twin integration across sectoral, disciplinary, and organisational boundaries.

In this vein, the Cambridge Centre for Digital Built Britain (CDBB) is in the process of developing and implementing an Information Management Framework (IMF) within the National Digital Twin Programme.[37] The IMF is part of the National Infrastructure Strategy.[38] The IMF aims to enable secure, resilient data sharing across the built environment, and consists of a Foundation Data Model (FDM), a Reference Data Library (RDL), and an Integration Architecture (IA).

By setting out a framework for connecting digital twins, the IMF aims to reduce the overall cost of point-to-point connections (bespoke, localized data-sharing connections between digital twins) and to improve the quality, consistency, and security of data-sharing across sectors with greater resilience and agility.

As the IMF builds towards an industry standard for creating interoperable systems data, strong digital twin adoption roadmaps in the UK should both incorporate methodologies for driving digital twin interoperability today and detail plans around how the course of adoption could be refactored to the IMF approach in the future.

While there are many different approaches emerging, the fundamental thing to remember is that enhancing interoperability is about getting the right flow of data and components that you require to tackle the problem your digital twin is looking to address.

Conclusions

- During the early stages of digital twin adoption, it is vital to employ methodologies that enable you to empathise with people and the business context, to define the problem that you are setting out to solve and, ultimately, set direction.
- The process of legally protecting your digital twin can quickly turn into a (highly costly) contractual ‘spider web’, and it is important to develop an agile, ethical approach to legally protecting your digital twin that minimises costs, but maximises opportunities for dynamic innovation.
- There is a need to determine the minimum level of information that you require to build a digital twin. Notably, there is an important differentiation to consider here– between what you require to get started, and everything you could possibly know.
- It is essential to ensure that digital twin adoption occurs in tandem with a systematic cyber security strategy broadly focused on data security and cybersecurity, dependability and resilience, information privacy, physical safety.
- Interoperability is a highly desirable characteristic of a digital twin, and early adoption roadmaps should take stock of existing methods that can be used to enhance interoperability, and to prepare to refactor, if necessary, to commonly accepted frameworks for interoperability.

Recommendation: Develop a cross-cutting, interdisciplinary coordinating body to drive forward digital twin adoption and diffusion in the UK

Core inputs (funding and people)

- 10-year public investment of £150 - £200 million focused on digital twin innovation, adoption, and diffusion (and the take-up of current and near-to market technologies) which would come as part of a broader programme of investment that would also enhance the UK's research, skills, infrastructure and core engineering capabilities
- Coordination from the Department of Business, Energy, & Industrial Strategy (BEIS) and UK Research & Innovation (UKRI)

Core activity

- 10-year public investment to develop a cross-cutting, interdisciplinary coordinating body designed to:
  - Bring diverse stakeholders together with UK industry to support the co-designing of inclusive, sector-level digital twin visions and adoption roadmaps
  - Identify common information requirements and capability gaps (that would need to be addressed by a broader programme of public investment) in the domains of: (i) net zero; (ii) built environment; (iii) public sector and public good; (iv) movement of people and goods, and; (v) productivity, manufacturing, and engineering
  - Incentivise (via tax credits or conditional innovation funding) the formation of multi-party agreements between diverse stakeholders and UK industry
  - Provide guidance on how to develop and implement common codes of conduct (covering minimum expectations around data use, the public functions of digital twins, and risk & uncertainty typologies) via supportive governance frameworks

Output

- A comprehensive, 10-year course of diversified investment that will drive the development, adoption, and diffusion of digital twins across 'mission-critical' domains (as part of a broader programme of investment)

Outcomes

- Increased take-up of digital twins across the UK by a broader range of people (using current and near-to-market technologies)
- Dramatically enhanced levels of collaboration between industry, academia, and Government across the UK's digital twin ecosystem
- Enhanced understanding of common information & capability gaps (associated with the foundational capabilities of a digital twin- 'sensing', 'understanding', 'deciding', and 'acting') that are presently inhibiting the rollout and connecting-up of digital twins in key domains
- Reduction of legal costs associated with developing and using a digital twin
- Enhanced delivery capacity regarding:
  - UK's net zero 2050 objectives
  - The reduction of regional and social inequalities
  - Accelerating R&D-led growth

10. Delivering on the UK's net-zero 2050 objectives

In this chapter, we focus in on the role that digital twins play in supporting the delivery of the UK's net zero 2050 objectives. We argue that digital twins can yield incremental environmental benefits as they are developed, and that they can be leveraged to **encourage decarbonisation, facilitate closures, downscaling, and environmental remediation**, and **de-risk and accelerate the integration of cutting-edge green technologies**. Long-term, this will help to drive the UK's comparative advantage in mission-critical domains and enable the UK to shine as an international exemplar for clean, sustainable development.

Actively encouraging decarbonisation

The prospect of negative impacts in carbon-intensive regions is not a reason to avoid or delay decarbonisation. Delay is fundamentally unjust.[39] The provision of space and support for transition planning is essential and can lower resistance to difficult decarbonisation pathways.

Digital twins can play a key role in this regard. They can be leveraged to **highlight practical steps** that different stakeholders in regions facing decarbonisation can take in anticipating change. They can also **expose trade-offs** between different stakeholders, supporting the development of inclusive decarbonisation strategies.

For instance, the Centre for Digital Built Britain (CDBB) is coordinating a world-leading 'National Digital Twin' programme (NDTP), building towards a connected ecosystem of digital twins that promises to facilitate a deeper understanding and more effective management of the complex trade-offs across the built environment which will be essential to achieving net-zero.[40]

Meanwhile, the Integrated Development of Low-Carbon Energy Systems (IDLES) programme at Imperial College London – a 5-year EPSRC-funded initiative which centres on whole-energy systems analysis – is currently developing tools that indicate optimal forms of future, integrated, energy systems to policy makers.[41]

As climate change takes hold, digital twins are also being deployed in the UK to help our coastal towns and river communities to adapt to mounting pressures. For instance, the Connected Places Catapult (CPC) is developing a digital twin of the River Thames that consists of a reliable and self-learning river level prediction tool for operational decisions and strategic planning, absorbing river influence data.[42] Considering factors such as depth, air draft, weather tide, extraction, this digital twin enables planners and operators to understand the future behaviour of the river, ensuring resilience and the mitigation of risks associated with climate change.

Facilitating closures, downscaling and the preservation of natural ecosystems

Primarily, it is worth considering the role that digital twins can play in enabling decision-makers to **monitor, manage, and preserve natural ecosystems.**

In Italy, a digital twin project known as 'ECOTWIN' is emerging that focuses on understanding natural ecosystems and relevant geosphere-biosphere interactions, with the goal of allowing the "exploration of the potential effects of climate and land-use change, pollution, and introduction of alien species before such forcing factors impact real ecosystems".[43]

In Finland, the Finnish Forest Centre has leveraged a digital twin track patterns of tree growth and recession across roughly 12 million hectares of private forest land. Through the application of a digital twin approach, decision-makers have been empowered to monitor and optimise supply chains, spot and prevent potential damage, and manage forests in virtual reality.[44]

At a planetary scale, the European Commission (EC) has also developed a flagship initiative named Destination Earth (DestinE)– a dynamic, interactive, computing and data intensive "Digital Twin of the Earth".[45]

Scheduled to be implemented gradually over the next 7-10 years, DestinE will enable different user groups to monitor natural eco-systems, simulate the impact of human activity on the natural world alongside patterns of environmental degradation, and to assess the socio-economic benefits of environmental legislation and policy.

Looking to the future, the DestinE initative as it is set to dramatically speed up the green transition and aid multinational planning for major environmental degradation and disasters. As such, it will be particularly crucial for the UK to maintains strong collaborative links with the initiative as we depart from the EU.

Moreover, to facilitate a just transition to net zero by 2050, the UK will also need to **close, downscale, and mitigate the risk of environmental damage** posed by the decommissioning of potentially hazardous industrial sites.

For instance, in the UK, Mott Macdonald is leveraging a digital twin to manage the decommissioning of one of the most complex nuclear facilities in the world, where small mistakes could prove environmentally hazardous, and site clean-up is expected to take more than 100 years.[46]

This project has laid the foundation for future cooperation with Japan around the decommissioning of legacy nuclear facilities and fusion facilities, and casts a light on how digital twins could be leveraged in the future to support decarbonisation.[47]

De-risking green technology investment

Digital twins can also dramatically de-risk and accelerate the development, deployment, and diffusion of cutting-edge green technologies, supporting the decarbonisation of energy production.

As it stands, the UK Government has recognised the importance of investing in low-carbon forms of energy production and green technologies, setting out a ten point plan that references a need to drive forward the adoption of important technologies (such as offshore wind, low carbon hydrogen, nuclear power, and innovative methods of carbon capture, usage, and storage).[48]

However, the cross-functional role that digital twins can play (in improving the through-lifecycle performance of green technologies) deserves much greater recognition in UK Government policy.

For example, while the UK's ten point plan recognises the environmental benefits associated with shifting to zero emissions vehicles by 2030 (presenting the challenge of rolling out thousands of high powered charge points), there is little mention of how digital twins could be used to the optimise the performance, arrangement, and distribution of future charging infrastructure upgrades.[49]

Similarly, in the domain of offshore wind, digital twins are set to revolutionise the operations and management of turbines and wind farms by enabling technicians and interdisciplinary teams to inspect the inner workings of turbines remotely, supporting planning around physical visitation and maintenance (see Box 1).

MIMRee Digital Twin (Thales and the Offshore Renewable Energy (ORE) Catapult)

MIMRee (Multi-Platform Inspection, Maintenance and Repair in Extreme Environments), a match funded Innovate UK project bringing together the collaborative efforts of a consortium including Thales and the Offshore Renewable Energy (ORE) Catapult, is an ambitious offshore wind robotics project with the aim of demonstrating an end-to-end autonomous inspect and repair mission for offshore wind farms. MIMRee includes an autonomous system capable of planning its own operational missions to offshore wind farms, performing inspections of moving turbine blades, and launching teams of inspection drones carrying blade crawlers for forensic inspection and damage repair.

Figure 7: Deploying repair robot onto wind turbine

MIMRee requires a safe and secure approach to the design, development, test and integration of cutting-edge maritime autonomy technologies. Many of the challenges presented by the MIMRee project can be resolved by the development and utilisation of two interoperable digital twins:

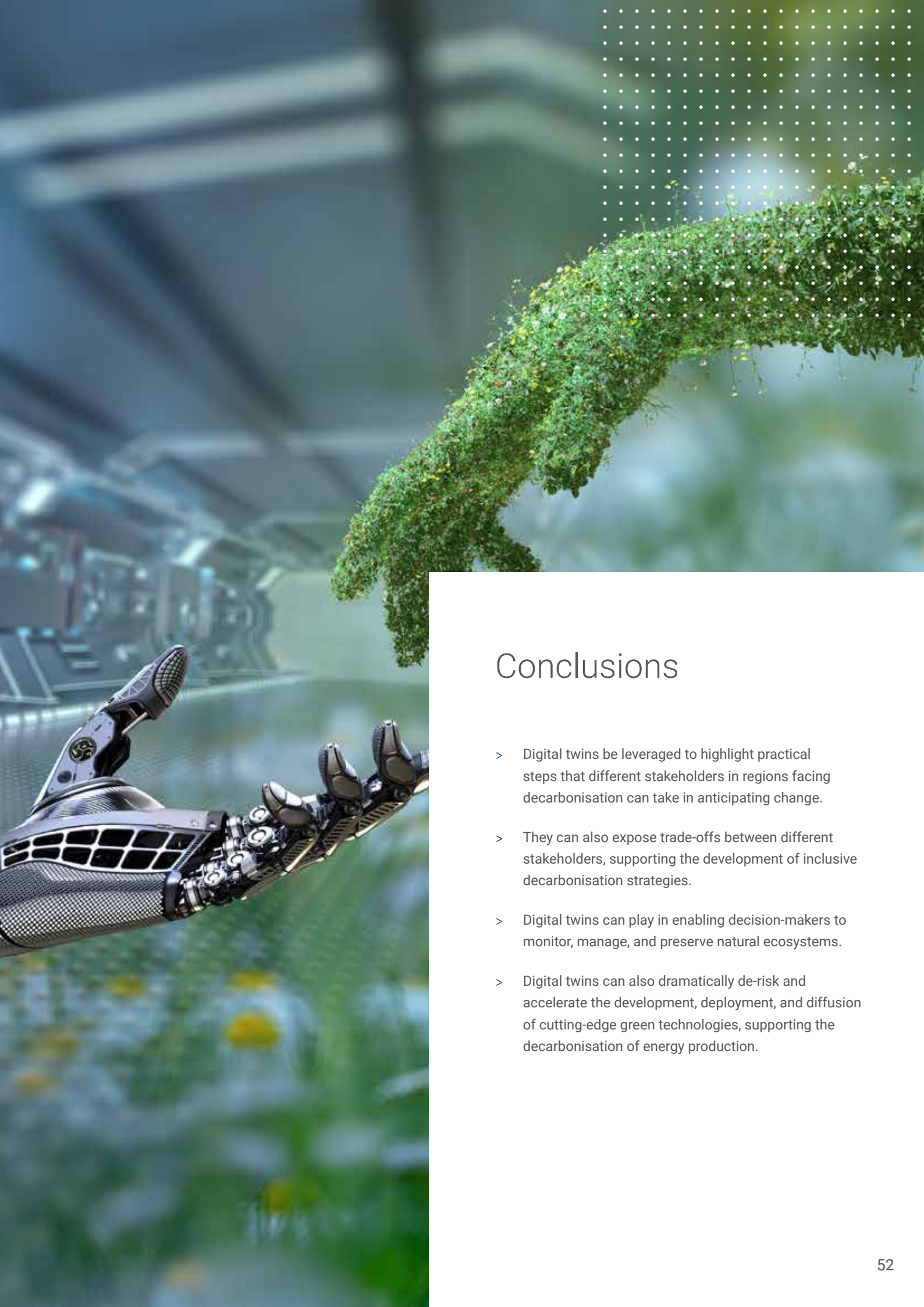
For the MIMRee project, Thales are developing an environment digital twin of Plymouth Sound, its autonomous systems and key infrastructure. The digital twin utilises multiple data feeds to create an up-to-date virtual representation of the maritime area and is used in the first instance for supervising autonomous vessels to aid with mission planning, execution and debrief (strategy and planning).

The Digital twin will accelerate the development, test, evaluation, and certification (assurance) of future autonomous systems operating in the maritime environment and any supporting infrastructure as part of an integrated system of systems, expediting the introduction of green technologies for Net-zero ambitions. The digital twin, in a Bayesian approach, will continually calibrate and optimise the systems performance (performance optimisation) with collected sensor data to increase fidelity and situational awareness, opening up opportunities that require higher fidelity, safe and secure environments for training and testing.

Figure 8: High fidelity virtual environments for robots deployment

In parallel, the ORE Catapult is developing the Synthetic Test and Unified Demonstration System (STUDS) – a Hardware-In-the-Loop interface that connects the multiple separate physical Robotics and Autonomous Systems (RAS) elements into a common high fidelity virtual environment (digital twin). The aim is to trigger the near real-world behaviour and inter-relationships between the nested autonomous systems in real time before they ever leave the bench. Beyond MIMRee, STUDS will form the core of a communications bridge that can be reconfigured for other robotics and autonomous systems. The vision is to support a truly mixed development and test environment – where robotic systems, data analysis, software solutions and end users interact in a real-time data driven utility scale simulation.

However, whilst the UK Government has committed to powering all UK homes via offshore wind by 2030 – which is anticipated to cost the UK taxpayer roughly £50bn[50] – the role that digital twins could play in supporting the rollout of wind farms remains relatively absent from major policy discussions.



Conclusions

- Digital twins be leveraged to highlight practical steps that different stakeholders in regions facing decarbonisation can take in anticipating change.
- They can also expose trade-offs between different stakeholders, supporting the development of inclusive decarbonisation strategies.
- Digital twins can play in enabling decision-makers to monitor, manage, and preserve natural ecosystems.
- Digital twins can also dramatically de-risk and accelerate the development, deployment, and diffusion of cutting-edge green technologies, supporting the decarbonisation of energy production.

Recommendation: Net zero 2050 digital twin demonstrator

Core inputs (funding and people)

- Demonstrator funding of £1.5 - £3million over 2021-2022
- Coordination from UKRI
- Strategic partnership with techUK's Digital Twins Working Group (DTWG)
- Strategic partnership with the Centre for Digital Built Britain (CDBB)

Core activity

- Funding a strategic demonstrator between 2021 – 2022 to demonstrate how digital twins can enhance the UK's global leadership in delivering on net zero 2050 objectives

Output

- A live demonstrator that will enable UK industry, the National Digital Twin Programme (NDTP), and the UK Government (BEIS, UKRI) to scope out the barriers and opportunities associated with deploying digital twins in order to accelerate decarbonisation

Outcomes

- Demonstrable decarbonisation benefits associated with the deployment of a digital twin (ideally in line with the COP 26 themes: clean energy, clean transport, nature-based solutions, adaptation &and resilience, finance)
- Improved understanding of the information and data required to build and scale digital twins in key application domains
- Reinforced industrial and technological capabilities in simulation, modelling, predictive data analytics, cloud, AI and HPC
- Improved understanding of the skills and areas of foundational research required in key application domain
- Improved understanding of existing standards and techniques used to integrate data sets and digital twins in key application domains
- Improved understanding of the different analytical requirements in key application domains

11. Addressing social inequalities

The pandemic has dealt a body blow to the UK's economy, with output falling by more than 10% in 2020.[51] In the wake of the pandemic, access to job opportunities, healthcare, education, and basic services has been tested to the limit, and existing patterns of social, economic, and geographical inequality have been exposed and reinforced.

Looking to the future, urgent action must be taken to address these inequalities and to ensure that the whole of the UK undergoes a dynamic recovery. In this chapter, we zoom in on the role that digital twins could play in enabling the UK to build a fairer society and level-up post-COVID.

Notably, we contend that digital twins can play a key role in **driving locally contextualised decision-making, in enhancing the efficacy of public spending and public services, and by enhancing connectivity between different regions.**

Driving locally contextualised decision-making

As the UK looks to respond, adapt, and thrive post-COVID, there is a need to ensure that decisions made about major, new industrial investments consider local assets and capacities.[52] As such, the notion that digital twins can play a role in enabling locally contextualised decision-making is gaining momentum.

Primarily, a growing body of evidence suggests that digital twins can **empower local citizens and communities to monitor the performance of major industrial investments** and to **hold key decision-makers to account.**

For example, the Active Building Research Programme has developed a user-friendly digital twin of a major housing development in Nottingham. The purpose of this digital twin is to engage and inform the residents, visitors and a wider audience about energy issues and the benefits of energy efficiency and community energy approaches.[53]

In doing so, the digital twin enables community-based review of energy systems underpinning the operation of residential housing, enhancing the accountability of those in charge of vital resources, and helping to drive behavioural change.

Additionally, digital twins are being deployed in the UK to streamline and **enhance methods of public consultation**. For instance, WSP have shown that a digital twin can enable design teams working on major infrastructure projects to engage with public stakeholders efficiently and effectively throughout the lifecycle of major transport infrastructure projects.

In this case, the use of a digital twin "provides a rich contextual record of feedback and proposals, their evaluation, and tracks how the scheme was modified through the consultation".[54]
In short, digital twins can be used to ensure that customers and stakeholders are valued and engaged over time, and that decision-making is grounded in up-to-date awareness of local concerns.

Looking to the future, the scale-up and diffusion of these kinds of digital twins could prove key to effective public consultation, and provide citizens in disadvantaged regions across the UK with the information they need, when they need it.

Enhancing public service management

The public sector is increasingly using new data-driven technologies to provide 'better public services', and there is growing recognition that public administrative data – data collected by or for public bodies for registration, transaction, and record keeping– might be used to enhance day-to-day operational decisions in the management and delivery of public services.

In line with this view, there is an emerging sense of optimism that digital twins may help to improve **the efficacy of public spending** and **decision-making**. In the wake of the Grenfell Tower tragedy, for example, there are growing calls to leverage digital twins to enhance the quality of social housing provision and, in doing so, protect some of the most vulnerable people in society.

Digital Twins for Social Housing (Urbanis and DiverseCity Surveyors)

In a post-Grenfell environ, the UK's social housing sector must urgently seek to unlock the untapped potential of data-driven asset management solutions and, increasingly, digital twins. Allied to the challenge of climate change and Net Zero 2050 targets, the Construction Playbook[55] has suggested that we must act now, and the UK's technology sector is primed and ready to positively disrupt the domain.

At the core of this effort is the pursuit of a measurable reduction in homelessness across the country. Through strategic collaboration with key partners (e.g. Action on Empty Homes)[56] there is an enormous opportunity to develop an ecosystem of connected twins for (and of) empty dwellings and the UK's public housing assets. The use of digital twins in this domain will drive social good, and precipitate a number of other socio-economic tangible benefits that could seamlessly synchronise with other local 'connected twins', including social, emergency and health care services.

The critical success factors to delivering an ecosystem of digital twins for empty dwellings, revolves around optimising the performance of key processes such as contract management; an area of particular concern in the UK.[57] Leveraged effectively, digital twins could also drive understanding of the causes of substandard performance of built assets- an area that has become mission critical for the housing sector where the need for 'black box' digital twins in asset management is pressing.

The 'black box' has been available to tell the story of both success and failure and, historically, has only been associated with the aeroplane. The information retrieved from such devices is similar to that now being sought by the Grenfell Tower Inquiry.[58]

Along with the tragic loss of life, a part of the construction industry died in that totally unnecessary tragedy too; many have said that the moral compass of the industry has gone for good, never to return. And, if it is to return, then [more rigorous] legislation i.e. the proposed Building Safety Bill; where at each of three stages [design, construction and occupation], owners will need to be clear as to who is responsible for managing the potential risks and what is required to move to the next stage.

If that goal is to be truly realised, enabling a 'golden thread' of vital asset information to be chronologically gathered and maintained over the assets whole-lifecycle, then digital twins will feature as an integral component of best practice.

Enhancing connectivity between regions across the UK

Another core dimension associated with addressing social inequalities and levelling-up relates to the need to deliver a connectivity revolution across the UK. This will involve driving connections between cities, within cities and beyond cities to poorly connected towns and rural areas.

The rollout of *digital* connectivity infrastructure across the UK is instrumental in achieving this and digital twins are already being deployed. For example, in Liverpool, CGA Simulation recently deployed a digital twin to plan the deployment of a 5G networking platform for Liverpool's Health and Social Care Testbed.[59]

This project has clearly showed that digital twins can be effective in enabling decision-makers to plot the optimal position for street-level mesh networks (mounted on lampposts and street furniture), helping to deliver affordable connectivity for homes in historically deprived areas around the UK.

Digital twins are also being leveraged to enhance physical connectivity between different regions across the UK. For instance, Toshiba recently collaborated with Greater Anglia to improve train timetables, helping to enhance the operational performance of major transport routes between towns, cities, and remote areas across the UK.[60] With this digital twin in place, those leading the project are now confident that the information gathered will be instrumental to rewriting future timetables and tracking stock and staff flows.

Deloitte Motion Simulator

Deloitte has developed a digital twin simulation solution, Motion Simulator, that enables organisations to make optimal strategic and operational decisions. This platform was first developed to help transport network operators to improve capacity, performance, and asset maintenance of their network through 'what-if' scenario simulations and has been delivering business benefits for over five years.

It is now being used for the re-validation of business cases for capital infrastructure projects in the transport sector through the simulation of future network models inside the digital twin. Motion Simulator is also used to model movement of goods and vehicles through ports and borders in the UK.

The Motion Simulator is a digital twin platform that is highly flexible in the creation of 2D and 3D replicas of real-world environments rapidly due to use of latest virtual simulation technologies and advanced artificial intelligence to model and predict 'what-if' scenarios.

Unlike most traditional simulation tools, which are designed to handle specific scenarios, Motion Simulator can answer new questions as the environment changes.

This, in the post-pandemic era, where things continue to be highly dynamic, makes it a critical decision support tool for businesses. Motion Simulator is capable of both predicting long term trends accurately with the use of historical data under stable conditions and short-term trends with precision using contemporary, low volume but 'effervescent' data under highly volatile conditions.

Motion Simulator can use and producing multiple industry standard data sets and as such can interoperate with other digital twins. It is also aligned to Gemini principles of the National Digital Twin strategy.

As the UK navigates through the pandemic, digital twins such as Motion Simulator will be essential to address short-term issues and to provide for future priorities that combines objectives associated with net zero, regional levelling-up, health, transport and labour markets.

These, in turn, will accelerate the growth of the UK economy overall by not only super charging innovation but also by creating a workforce of Digital and AI experts.

Beyond the UK's rail network, digital twins are also driving improvement in road connectivity across the UK. Indeed, digital twins are fast becoming a realisation for many UK road asset owners, enabling enhanced delivery through all stages of road asset lifecycles (from design to construction and beyond). In particular, the delivery of major infrastructure schemes such as Thames Tideway Tunnel, HS2 as well as numerous Highways England schemes have improved as a result of taking a digital twin approach, with notable benefits relating to better asset information, greater efficiency, higher quality as well as health and safety benefits.[61] In Yorkshire and Humber, digital twins are also being used to boost the capacity of existing transport networks between Leeds, York, and Hull helping to reduce congestion and air pollution.[62]

Conclusions

- Digital twins can support levelling-up by driving locally contextualised decision-making, empowering citizens to monitor the performance of infrastructure investments and supporting more effective public consultation.
- Digital twins can help to address social inequality by enhancing the efficacy of public spending and decision-making, particularly in areas such as healthcare and social housing.
- Digital twins can be leveraged to support inter-regional collaboration by driving upgrades in connectivity infrastructure (especially in domains like energy, travel and transport, healthcare- which are all intimately connected).

12. Accelerating R&D-led growth

In the wake of the COVID-19 pandemic, the UK Government faces the enormous challenge of increasing UK investment in R&D to 2.4% of GDP by 2027 and of increasing public funding for R&D to £22 billion per year by 2024 to 2025.[63] This will take a monumental effort from industry and Government and depend on whether the UK can build on strong national-level capabilities (in areas like artificial intelligence (AI), quantum computing, and mathematics) in order to deploy trusted and secure constellations of digital twins in entirely new domains.

In this light, the UK must not become complacent and fail to recognise the role that digital twins can play in accelerating R&D-led growth- an increasingly an intense point of interest for scientists, researchers, and those at the forefront of developing new, emerging technologies across the UK.

Triggering the diffusion of digital twins will help innovators to bring transformative applications to market faster by enabling faster, cheaper prototyping, turbo charging collaborative innovation and continuous evaluation, and strengthening research infrastructure and innovating at the limits.

Long-term, this will enable the UK to become a science and technology superpower, deliver economic growth and societal benefits across the UK, and provide the foundations for the new industries of tomorrow.

Faster, cheaper prototyping

Digital twins are gaining significant traction as R&D 'accelerators' because they can streamline product designing and eliminate onerous aspects of traditional prototyping, lessening the need for expensive tests in the real-world and increasing the speed of bringing commercially viable R&D projects to market.

Spirent's 5G Network Digital Twin: Concept and Usage

5G is a major step forward towards all-purpose networks. With its agnostic access, high reliability and low latency, technologies with 5G connectivity are building the foundation towards new smart and innovative applications.[64] As a new technology, 5G is also the enabler for multiple verticals and industries, such as automotive, logistics, smart factories, railways, health, and lots more.

With 5G still in its infancy and lots of the promised features still to come, the challenge for industry is how to test and validate real-world scenarios for a network that only currently sees a small fraction of its future usage. One such industry is automotive, where 5G is seen as the foundation towards enhanced 'vehicle-to-everything' (V2X) communication and the future evolution of autonomous driving.

Spirent is making testing of real-world scenarios possible by utilising a new and agile approach: the 5G Network Digital Twin.[65] A replica of a real 5G physical network and its multiple components, the 5G Network Digital Twin allows for continuous prototyping, testing and optimization across a variety of potential situations. The primary goal is to provide a flexible and future-proofed Digital Twin enabled for 5G connectivity which enables simple, repeatable and predictable prototyping and "what-if" scenarios in stable environments.

Autonomous driving (as a long-term goal for developing mobility) requires low latency, high reliability, and bandwidth for communication towards infrastructure or peers, and 5G networks can provide major components to address such need. There will be multiple types of applications in communicating cars, providing opportunities for start-ups, SME's and traditional players to enter the market with new solutions, contributing to increased business in the V2X industry.

However, each application will have its own needs and requirements, and the successful introduction of an application will require deep validation and testing to avoid later bottlenecks and issues in real-life environments.

The V2X Digital Twin can be used together with real components, such as car modems, end-user devices, cell or core network elements to validate 5G connectivity for V2X. With the flexibility provided, there are potentially limitless configurations and use cases that can be created, helping to reduce risk by safely testing "what-if" scenarios, cyber-attacks, optimizing decision making by modelling unlimited configurations, and improving reliability by identifying design weaknesses and opportunities, and optimizing networks.

Figure 9: 5G Network Digital Twin

The 5G Network Digital Twin provides significant benefits[66], giving easy access to an agnostic testbed, combined with high flexibility to run configurations and scenarios. It also provides cost and operational efficiency benefits and enables the building of eco-systems with academia and industrial partners that can accelerate research and time to market.

In the real-world, there are many applications of digital twins for rapid prototyping. Throughout the COVID-19 pandemic, for example, Siemens have drawn on a digital twin approach to significantly reduce development times for the designing and manufacturing of respiratory masks, removing the time-consuming process of building and testing physical prototypes.[67] Using digital twins in this way has reduced development times, helping to save lives and supporting the UK's recovery from adverse health implications of the pandemic.

Elsewhere, in the aerospace and defence sector, digital twins are being used to speed up the validation of safety-critical applications. For example, BAE Systems have used a digital twin approach to reduce testing times associate with the rollout of advanced mine neutralisation systems, enabling users to explore the effects that increased payloads can have on important factors such as range and handling.[68] In this case, adopting a digital twin approach has reduced the time and cost associated with impact testing and driven the design of new in-service support offerings.

In the pharmaceuticals sector– where the cost of developing new drugs can reach into the billions and preclinical testing phases take an average of three and a half years– Oklahoma State University have developed a digital twin of an aerosol drug to explore how it can target lung tumours. In this case, scientists identified that they could increase the number of particles reaching their target from 20% to 90%, sparing them the need to create several prototypes and, ultimately, shortening the testing process.

At a systems-level, digital twins can also eliminate the need for physical experimentation while optimising the performance of key assets and processes and driving significant cost savings. For instance, Accenture worked with Ireland's An Post, a public postal service, to create a digital twin of its hundreds of vehicles, delivery routes, multiple sorting centres, and different processes to evaluate the impact of new technologies and test new approaches on throughput and timeliness.[70]

Turbo charging collaborative innovation and continuous evaluation

In most domains, complex products and services are only usually analysed, piece by piece, when they are created or when they come to the end of their useful life. Through the adoption of a digital twin approach, however, innovators have a live window into the product or service- enabling continuous monitoring, evaluation and updating.

There are many examples of this in practice. For instance, Tesla creates a digital twin of every vehicle it sells which are so effectively integrated that maintenance issues can be fixed with software updates – for instance, adjusting the hydraulics to compensate for a rattling door.[71]

Moreover, the capacity of digital twins to show real-time comparisons between actual and ideal states and behaviours in the real-world presents an enormous opportunity for innovators around the world to collaborate remotely and supports the rollout of new platform-as-a-service (PaaS) business models.

In the UK's mobility sector, for instance, several applications for digital twins for learning and productivity have been identified. For example, across pilots at Network Rail, HS1 and HS2, Crossrail and TfL, digital twins have been shown to enhance skills, training and competency management – providing engaging opportunities for professional training that would otherwise need to be learnt in situ.[72]

In addition, digital twins have been leveraged across the same projects to "imagine the world of expectation for 21st century passengers, their travel requirements and the impact that a station has on their experience". As such, the use of digital twins has made staff more innovative and empathetic to end-user concerns. These are enabling conditions that will accelerate the implementation of major transport infrastructure projects and help to drive public acceptance in the sphere long-term.

Looking to the future, employing similar approaches across other sectors and challenges will help to improve the UK's productivity, strengthen public engagement with transformational infrastructure upgrades, and enable decision-makers to learn collaboratively, without the need to travel to physical sites directly.

Strengthening research infrastructure and innovating at the limits

Finally, digital twins have a significant role to play in enhancing the quality of research and innovation (R&I) infrastructure in the UK. For example, drawing on international exemplars, digital twins are being used to drive efficiencies at an advanced manufacturing technology testbed in Singapore helping to ensure that the performance of innovation infrastructure is maintained to a high degree.[73]

Similarly, digital twins are playing a role in enabling innovation around the world in situations where it may be unethical, highly risky, or counterproductive to run experimental physical tests.

Building on this notion digital twins are being deployed in healthcare to model the human heart, helping clinicians diagnose cardiovascular diseases up to 80% faster and with fewer variations than traditional methods allow.[74]

This is raising expectations that digital twins can be used to drive innovation in areas where it may be unethical to run physical experiments, with transformative implications for people across the UK.

Conclusions

- Digital twins can accelerate R&D-led growth in the UK by supporting innovative ideation, designing, and testing of new products and services.
- Digital twins can turbo charge collaborative, immersive innovation through enabling remote learning, training, and re-skilling, and support continuous evaluation.
- Digital twins can de-risk investment in UK-based research infrastructure, supporting facilities upgrades, and can facilitate ‘innovating at the limits’.

Recommendation: Demonstrate value from (and explore barriers to) the adoption and diffusion of digital twins via strategic demonstrators

Core inputs

- £1.5- £3 million per demonstrator between 2021 – 2024

i. High-level of ambition = 4-6 demonstrators per domain

ii. Minimum level of ambition = 2-3 demonstrators per domain

- Coordination from UKRI and strategic engagement with techUK's Digital Twin Working Group (DTWG) to scope out feasibility of different demonstrators

Core activity

- Fund a series of strategic demonstrators from 2021- 2023 to highlight how value can be derived from digital twins across the following five domains:

iii. Enhancing the UK's global leadership in delivering on net zero 2050 objectives (bringing together the UK's world-leading geospatial community and those focused on building digital twins of the UK's natural environment)

iv. Driving sustainable outcomes across the UK's built environment by supporting the continued development of the CDBB's Information Management Framework [IMF] (which will provide an early blueprint for other domains)

v. Enhancing the day-to-day operational decisions in the management, delivery and observation of public agencies and outsourced social services (emphasis should be placed on integrating digital twins applied to three key areas: social housing, healthcare, and childcare)

vi. Facilitating the safe return of passengers to clean modes of public transport as the UK emerges from the COVID-19 pandemic (building on existing national-level transport and mobility digital twin initiatives)

vii. Accelerating the rollout of 'factory' digital twins and the scaled deployment of smart machines and robotics across the UK's advanced manufacturing sector

Output

- A diversified portfolio of public investment that will enable the UK Government to scope out key areas where further investment and support will be needed

- Demonstration that digital twins (developed from current or near-to-market technologies) can deliver transformational positive externalities in the real-world

Outcomes

- Improved understanding of the information and data required to build and scale digital twins in key application domains

- Improved understanding of the skills and areas of foundational research required in key application domains

- Improved understanding of existing standards and techniques used to integrate data sets and digital twins in key application domains

- Improved understanding of the different analytical requirements required in key application domains

13. Concluding remarks

Looking to the future, urgent, sustained, and collective action will be needed to reignite different layers of our economy and society. This report outlines how digital twins can be adopted effectively to cope with unprecedented levels of risk and uncertainty, and why targeted support for the UK's digital twin ecosystem will unlock value for our people, economy, society, and planet.

In Chapter 1, we have presented a flexible and dynamic definition of a digital twin that can be used across a wide variety of different sectors and problem domains. To reiterate, we define a digital twin as:

> ***A relevant, virtual representation of the state and behaviour of something physical or non-physical with a functional output in the real-world.***

We also run through the different foundational technical elements of a digital twin (sensors, data, integration, analytics, actuators) and highlight why the adoption of a multi-criteria assessment framework can be useful for assessing the level of capability associated with a digital twin.

Critically, we present a clear 'use case' framework, which highlights different types of digital twins related to strategy and planning, performance optimisation, assurance. Again, we also point out that employing a robust, multi-criteria assessment framework (grounded in awareness of the decision-making context at hand) can enable the prioritisation of use cases.

Beyond the core use case, which may evolve over time, we also recognise that digital twins may be characterised by their degree of complexity, and the stage of lifecycle integration.

In Chapter 2, we provide advice for those interested in building early digital twin adoption plans. The advice we provide is not sector or domain-specific, but we set out a set of general principles and methodologies that, if followed, can ease the process of digital twin development and adoption.

Here, we stress that early adoption planning is critical to gaining buy-in, generating enthusiasm for an idea, and will dramatically the improve odds of success when it comes to raising capital, and sustaining support for a digital twin.

We also point out that here is no definitive set of skills that a digital twin initiative must rely on, but effective teams will blend domain expertise, interdisciplinary working environments, and involve diverse individuals that have the capacity to think in 4D, over time

When considering the opportunity associated with a digital twin, there is also a need to look beyond the immediate opportunities and recognise that there are evolving ideas of what success really means. Moreover, it is vital to address factors (such as interest rates, regulations, or industry standards) that will inevitably change but that cannot be directly controlled.

In Chapter 3, we cover the core elements of a strong early adoption roadmap. Here, we suggest that it is vital to employ methodologies that enable you to empathise with people and the business context, to define the problem that you are setting out to solve and, ultimately, set direction.

We also indicate that the process of legally protecting your digital twin can quickly turn into a (highly costly) contractual 'spider web', and it is important to develop an agile, ethical approach to legally protecting your digital twin that minimises costs, but maximises opportunities for dynamic innovation

As a digital twin adoption roadmap takes shape, there is also a need to determine the minimum levels of information that you require to build a digital twin. Notably, there is an important differentiation to consider here– between what you require to get started, and everything you could possibly know. It is also vital to consider the value of meta data and semantic modelling and designing for extensibility.

We also stress the importance of ensuring that digital twin adoption occurs in tandem with a systematic cyber security strategy broadly focused on data security and cybersecurity, dependability and resilience, information privacy, physical safety.

In the same chapter, we acknowledge interoperability as a highly desirable characteristic of a digital twin and suggest that early adoption roadmaps should take stock of existing methods that can be used to enhance interoperability, and to prepare to refactor, if necessary, to commonly accepted frameworks for interoperability.

Drawing the report to a close, Chapters 4, 5, and 6 highlight the 'prizes' to be won through the scaled development, adoption, and diffusion of digital twins across the UK.

In Chapter 4, we outline how digital twins can be leveraged to highlight practical steps for stakeholders and expose trade-offs between different stakeholders, supporting the development of inclusive decarbonisation strategies.

We also highlight that digital twins can play a key role in enabling decision-makers to monitor, manage, and preserve natural ecosystems. Thirdly, we show that digital twins can dramatically de-risk and accelerate the rollout of cutting-edge green technologies.

In Chapter 5, we state that digital twins can support levelling-up by driving locally contextualised decision-making, empowering citizens to monitor the performance of infrastructure investments and key decision-makers to engage in more effective and meaningful public consultation. We also identify that digital twins can be used to enhance the efficacy of public spending and decision-making, supporting the case for digital twins across mission-critical domains, such as the UK's social housing sector. Moreover, we recognise the need to bring different parts of the UK together and suggest that digital twins can drive upgrades in physical and digital connectivity infrastructure.

Finally, in Chapter 6, we show that digital twins can accelerate R&D-led growth in the UK by supporting innovative ideation, designing, and testing of new products and services. We also suggest that Digital twins can turbo charge collaborative, immersive innovation through enabling remote learning, training, and re-skilling, and support continuous evaluation. Lastly, we demonstrate that digital twins can strengthen the UK's research infrastructure and enable innovation at the limits.

In sum, there is an incredible opportunity to use digital twins for good- and this report provides a reference point for those considering how digital twins can be adopted and why digital twins are critical to the UK's future success.

Looking to the future our hope is that this report will provide an accessible resource for a wide cross-section of society. People should feel empowered to build out their own adoption plans and roadmaps.

In doing so, they will undoubtedly face hard questions- especially during the early phases of each unique digital twin journey. Yet those who do pose these critical questions and seek to provide answers will help to unlock value across the UK's digital twin ecosystem, to the benefit of generations to come.

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