Digital twins for the built environment

An introduction to the opportunities, benefits, challenges and risks

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Foreword

Increasing population, economic growth and climate change are all putting significant pressure on infrastructure. To address this, the UK's existing infrastructure needs to become smarter: working as an optimised system that reduces disruption and congestion.

Since the publication of the National Infrastructure Commission's Data for the Public Good report[1], the Centre for Digital Built Britain (CDBB) has been working to understand how digital twins, and a National Digital Twin (NDT), can address this challenge.

Across the industry, from asset owners and operators to designers and contractors, the national Building Information Modelling (BIM) mandate has provided a foundation of mature information management. BIM enables us to construct an asset digitally before stepping on site, so that we can build faster, safer, and greener with less disruption.

As we look to improve whole-life value, we must tackle the question of how we can use this culture of secure information management to create digital twins of physical assets. The transformative potential of digital twins lies in connecting them together, providing greater insight through wider context. CDBB's vision for the national digital twin is an ecosystem of connected digital twins that have evolved with shared vision and values.

CDBB is delivering the information management framework to facilitate the secure, resilient data sharing between digital twins.

At the heart of the framework, CDBB envisages a national resource, held in common, that enables secure, resilient data sharing across the built environment, which we have called 'the Commons'. If we work together to ensure a common approach to secure, resilient data sharing in digital twins, the value of all of our information will grow.

In 2018 CDBB published the Gemini Principles[2] to begin enabling alignment on the approach to information management across the built environment Establishing agreed definitions and principles from the outset will make it easier to share data in the future.

These principles are effectively the conscience of the information management framework and the national digital twin. To ensure that these two initiatives are – and remain – for the public good, they need strong founding values to guide them.

Enshrined in these values is the notion that all digital twins must have clear purpose, must be trustworthy and must function effectively. All the Gemini Principles flow from this. They are deliberately simple, but their implications are far-reaching and challenging. They are descriptive of intent, but agnostic on solutions, encouraging innovation and development over time.

As you and your organisations begin or continue on your digital transformation, we urge you to hard-code the values of the Gemini Principles into your information management strategy.

We recognise that for digital twins to serve all of society they will need to be created by a community. We must work together with a shared vision, sharing lessons alongside data. CDBB, through its Digital Framework Task Group (DFTG) and its Digital Twin Hub, is working to foster a community where early adopters can learn by doing and progress by sharing. We hope you will join us.

We welcome this white paper from the Institution of Engineering and Technology (IET) and Atkins and its work in highlighting how digital twins can address the challenges facing the built environment.

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1. Executive summary

Digital twins are rapidly becoming perceived as *must haves* in engineering. As digital replicas of real-world infrastructure, the potential benefits are easy to grasp: a direct application of computing power to complex, tangible problems in the physical world. Useful across industries, they can bring greater accuracy, control and predictability to a range of challenges.

The global digital twin market was valued at USD $3.8bn in 2019 and is expected to reach USD $35.8bn by 2025[3]. Half of all large industrial companies are predicted to be using them in some form by 2021, which is expected to result in a 10% increase in effectiveness[4].

Whilst a fully responsive, automated holistic system is currently a distant goal, industry is already delivering easily adoptable starter elements. Even these small steps add value and as technology and techniques improve, we predict the convergence of these individual parts and emergence of much more complete, connected twins,ultimately moving toward networks of interconnected models for entire countries.

Digital twins promise more effective asset design, project execution and asset operations. By dynamically integrating data and information throughout the asset lifecycle, they will offer short and long-term efficiency and productivity gains. More than just BIM or a 3D model, twins are a data resource that can improve the design of new assets and understanding of existing asset condition, verify the as-built situation, run 'what if' simulations and scenarios, or provide a digital snapshot for future works. This has the potential to vastly reduce errors and discontinuities present in more traditional methods of information management.

Breaking down distinctions between the physical and digital, it's easy to see why digital twins capture the imagination. So, what's the catch? Most proponents are excellent at selling their potential, but constant disagreement on what features or elements comprise a digital twin makes the path towards development and understanding value difficult.

To help this debate we propose a clear, industry-agnostic, maturity spectrum to define the elements and requirements of a digital twin, and to provide a framework for communicating the complex concept. This paper summarises the spectrum and outlines three key applications that are considered to bring the highest overall benefit to the built environment.

This paper also highlights the latest developments in the UK built environment, driven by the NIC (National Infrastructure Commission) and CDBB. We acknowledge that other industry sectors and countries are also making significant progress. Some of these will be addressed in later works.

2. Introduction – what is a digital twin?

The term digital twin has entered the regular vocabulary of all industry sectors. It's almost always used as an example of revolution and is considered fundamental to transformation, but the broad scope of the concept makes a common definition difficult. Yet, it is only once we understand and demystify the idea and can see a path to making it a reality that we will start to appreciate its benefits.

Our industry too commonly focuses on (and prematurely attempts to sell) an idealised 'unicorn' conception of what a twin could achieve if fully implemented, despite this currently being cost-prohibitive. Few refer to the milestones along the journey, or incremental value-proving developments.

This is evidenced, in part, by the fact that to date only 5% of enterprises have started implementing digital twins and less than 1% of assets have one[5].

With that in mind, this paper attempts to demystify the concept and break through the platitudes, answering the fundamental questions: Why do we need them? How will a digital twin generate value? And will it support better decision making?

2.1. Defining the digital twin

Digital twins are symptomatic of the broader trend toward digitalisation that is having a profound effect on businesses and society.

Widely cited as the fourth industrial revolution or industry 4.0 (following: steam power [c1760-c1840], electricity [c1870-c1914] and microchips [c1970]), it's characterised by a fusion of technologies that blur the lines between the physical, digital, and biological spheres – such as artificial intelligence (AI), machine learning (ML), robotics, autonomous vehicles and the Internet of Things (IoT). Though the exact dates of the earlier revolutions are disputed, their timeframes were undoubtedly slower than the rapid pace and scale of today's disruption, and still they saw companies and individuals reluctant to embrace change.

The Gemini Principles[2] define a digital twin as *"a realistic digital representation of assets, processes or systems in the built or natural environment"*.

Many people see it as a simple digital replica of a real thing – a 'twin', but *"what distinguishes a digital twin from any other digital model or replica is its connection to its physical twin"*, with 'connection' meaning there is some type of relationship and association between the physical and digital. Therein lies the complexity of this industry-agnostic concept.

Depending on its maturity, this twin can range from a simple 2D or 3D model of a local component, all the way to a fully integrated and highly accurate model of an entire asset, facility or even country (such as the UK National Digital Twin programme[2]), with each element dynamically linked to engineering, construction, and operational data.

This broad range of what a twin can be has made defining and understanding them extremely difficult, with disagreement on what level of maturity or features represent a 'true' twin. BIM, Building Lifecycle Management (BLM) and Product Lifecycle Management (PLM) represent similar concepts with some important distinctions, that are all part of data generation and information management – a theme fundamental to the twin.

The concept of a digital twin has existed in various forms since early space exploration, where it was referred to as a "mirrored system" and first used by NASA nearly 50 years ago to rescue the Apollo 13 mission[6]. The term "digital twin" appeared in the early 2000's, an evolution of PLM[7]. Since then, its meaning has developed from simply defining a PLM tool, to an integral digital business decision assistant and agent for new value and service creation.

Digital twins bring a wealth of useful applications across the construction market and lifecycle of asset, standing as a bridge between the physical and digital. As sensors become smaller and more affordable, the ability to gather, process and communicate information increases, making the interface between the two worlds invaluable.

2.2. Opportunities and benefits

The global digital twin market was valued at USD $3.8bn in 2019 and is expected to reach USD $35.8bn by 2025[3]. Gartner predict that half of all large companies will use some form of one by 2021 – resulting in a 10% improvement in effectiveness[4].

Irrespective of how various analysts communicate value, they all anticipate one thing – significant growth and importance of the digital twin. The infrastructure and construction sectors, along with their supply chains, are all now looking to harness that potential.

There is no single solution or platform used to provide a digital twin, just as there is not one CAD package used to create a drawing or a 3D model. It's about the process and methodology, not the technology. It's leveraging experience-based wisdom to manage and manipulate a multitude of datasets.

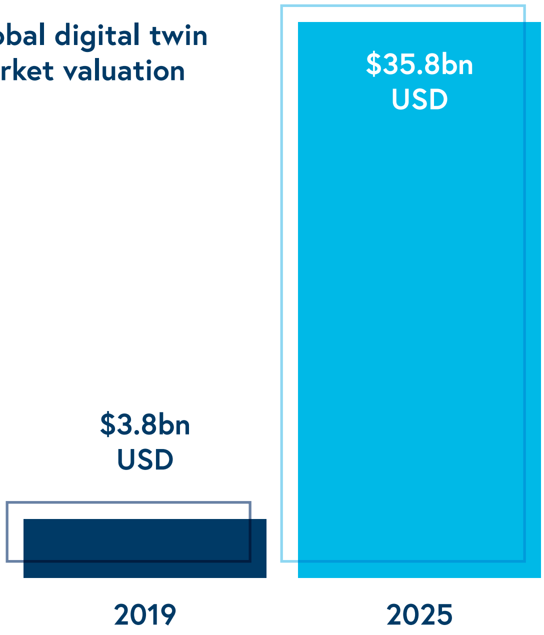
Whilst a fully responsive, automated holistic system is currently a distant goal, industry are already delivering easily adoptable starter elements. Even these small steps add value and as technology and techniques improve, we predict the convergence of these individual parts and emergence of much more complete, connected twins. Ultimately moving toward networks of interconnected models for entire countries.

The aim is to create a 'single *version* of truth' for an asset, where all data can be accessed and viewed throughout the design-build-operate lifecycle. This is distinctly different from a 'single *source* of truth', as a digital twin is about using a constellation, or ecosystem of technologies that work and connect.

Inevitably the aggregation of this data also creates a security risk, particularly for critical national infrastructure. Likewise it creates a need to validate and authenticate data and prevent unauthorised changes, which is compounded in situations with multiple parties and sources. This complex topic is not discussed in detail within this paper, but notes some interesting research into independent stewardship of data[8].

The digital twin promises more effective asset design, project execution and asset operations by dynamically integrating data and information throughout the asset lifecycle to achieve short and long-term efficiency and productivity gains. It's a data resource that can improve the design of a new asset or understanding of existing asset condition, to verify the as-built situation, run 'what if' simulations and scenarios, or provide a digital snapshot for future works. This has the potential to vastly reduce errors and discontinuities present in more traditional methods of information management.

Global digital twin market valuation



Given its key importance, the value of digital twin data should be recognised on the balance sheet, alongside the asset it twins. Return on Investment (ROI) could be given by comparing the costs associated with creating the twin against savings generated over the life of the asset[9].

As asset owners pivot away from document silos and toward dynamic and integrated data systems, the digital twin will become like a node in a network, alongside potentially many other twins for different assets or systems. Dynamic and accurate (like any corporate financial or HR system), it should represent a living, as-built version of the operating asset, delivering value to the business.

Table 1 summarises the main benefits that adopting a digital twin approach can bring to the construction industry and built environment.

Reduce construction and operating costs	Virtual scenarios on construction sequencing and logistics can be run and visualised, familiarising workers with required tasks and reducing costly re-works. Through data-driven decision-making, and AI/ML, they can predict maintenance activities and events, which in turn will help navigate unexpected interventions and ultimately streamline costs throughout the asset's operational life.
Increase productivity and collaboration	Vital information about the built asset can be stored and analysed throughout its lifecycle, and kept current. This information (such as design documentation, inventories, material specifications, and programmes/schedules) can be easily accessed and used to assist decision making and de-risk project execution.
Improve safety	On-site workers can get real-time tracking and alerts about the site, including hazardous area notifications and emergency situation response instructions.
Optimise asset performance and sustainability	Operational and occupational data can be monitored and analysed in real-time, providing valuable insights on how the asset is used and currently performing. This provides the ability to answer questions, such as: Where are the highest risk maintenance items? alongside determining scenarios such as: If I change X how will it impact Y? These insights can be fed back to designers for better, more efficient built assets in the future – helping countries meet obligations to UN Sustainable Development Goals (SDG)[10].

Table 1 – summary of main benefits that digital twins can bring to the built environment

2.3. Policy

In the UK policy is developed to support the adoption of digital twins for the built environment. Data for the Public Good, a report published by the National Infrastructure Commission (NIC) in 2017, is one of the key documents extolling the value of embracing digital twin technology[1]. The report suggests that through collecting the right data, setting standards and sharing data securely for the public good, the UK could release an additional £7bn in benefits per year across the infrastructure sector. This is equivalent to 25% of the total UK infrastructure spend.

Through recommendations of the NIC, in 2018 the UK Government's new Digital Framework Task Group (DFTG) published the Gemini Principles to guide the creation of a National Digital Twin (NDT) – an ecosystem of digital twins connected by securely shared data (Figure 1)[2].

The aim is to improve the performance, service and value of the UK's infrastructure; delivering benefits to society, business, the environment and the economy.

The foundations that the Gemini Principles set out to establish are applicable to all industry sectors. Governments must take the lead and drive national policy to create shared frameworks and ecosystems.

Purpose: Must have clear purpose	**Public good** Must be used to deliver genuine public benefit in perpetuity.	**Value creation** Must enable value creation and performance improvement.	**Insight** Must provide determinable insight into the built environment.
Trust: Must be trustworthy	**Security** Must enable security and be secure itself.	**Openness** Must be as open as possible.	**Quality** Must be built on data of an appropriate quality.
Function: Must function effectively	**Federation** Must be based on a standard connected environment.	**Curation** Must have clear ownership, governance and regulation.	**Evolution** Must be able to adapt as technologu and society evolve.

Figure 1 – the Gemini Principles, courtesy of CDBB[2]

3. Digital twin maturity spectrum

Process and methodology are key to developing and managing digital twins for the built environment, as is remembering their relevance to the entire asset lifecycle. Their creation and management are a journey, and while a twin can be developed at any point in an asset's life, it's most effective when deployed at an early stage, so that captured data adds value for longer.

It's easy to be distracted by a unicorn-like concept of what a twin could achieve if fully implemented, despite this being largely unachievable and/or cost-prohibitive today. Instead we should more usefully focus on purpose, understanding the benefits of each milestone and how value is increasing along the journey to maturity.

To help achieve this, we propose an industry-agnostic maturity spectrum. This defines the different elements and provides a framework to communicate progress[11] as illustrated in Figure 2.

As a twin develops, each element increases in complexity and connectivity, and subsequently value. **It's important to note that these elements are not necessarily linear or sequential, so a twin might possess features of higher-order elements before lower-order ones.** However, complexity is best considered logarithmically, whereby the higher-order elements are significantly more complex than the lower-order, foundational ones (Table 2).

It's essential that the purpose and value of increased complexity and connectedness are clearly identified, justified and realised, which relies on effective implementation and management.

The physical and digital are securely connected via a constellation of data platforms or aggregators. This enables data from asset management systems, document management systems, common data environments, data historians and so forth, to come together in support of new business scenarios.

> While a twin can be developed at any point in an asset's life, it's most effective when deployed at an early stage, so that captured data adds value for longer.

The ability to run simulations answering 'what if' questions, and to interrogate and analyse the data to inform management of physical assets, is a key part of the digital twin. This is a capability that's possible across every element of the maturity spectrum (see 3.1).

As we move through the maturity spectrum, each of the elements further enables removing humans from hazardous processes or tasks, intrinsically improving safety.

Maturity element (logarithmic scale of complexity and connectedness)	Defining principle	Outline usage
0	– Reality capture *(e.g. point cloud, drones, photogrammetry, or drawings/sketches)*	– Brownfield (existing) as-built survey
1	– 2D map/system or 3D model *(e.g. object-based, with no metadata or BIM)*	– Design/asset optimisation and coordination
2	– Connect model to persistent (static) data, metadata and BIM Stage 2 *(e.g. documents, drawings, asset management systems)*	– 4D/5D simulation – Design/asset management – BIM Stage 2
3	– Enrich with real-time data *(e.g. from IoT, sensors)*	– Operational efficiency
4	– Two-way data integration and interaction	– Remote and immersive operations – Control the physical from the digital
5	– Autonomous operations and maintenance	– Complete self-governance with total oversight and transparency

Table 2 – digital twin maturity spectrum defining principles and outline usage[11]

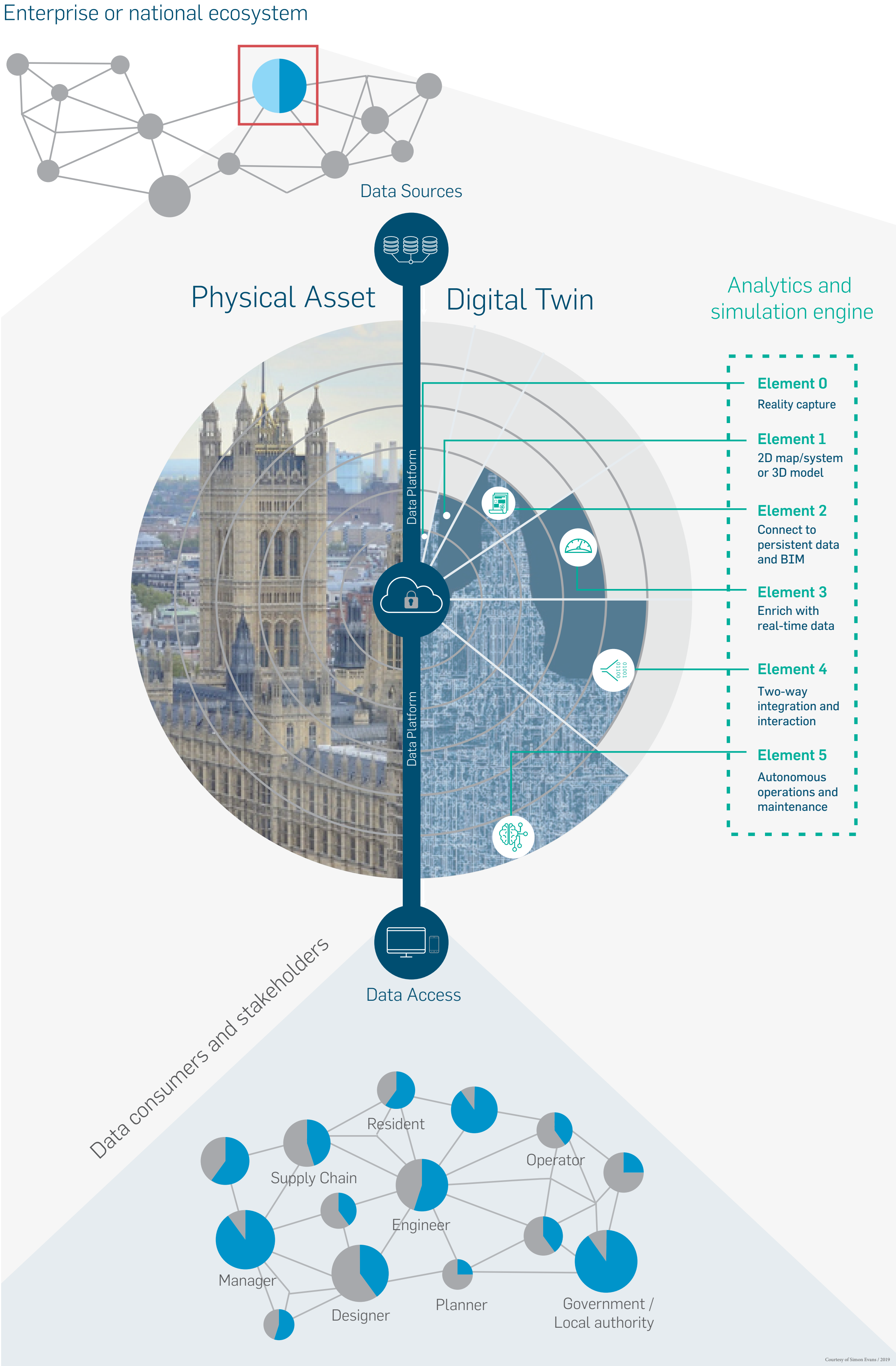


Figure 2 – digital twin maturity spectrum[11]

Element 0

Reality capture (for existing physical assets)

The lowest order element to start a digital twin (relevant only on existing physical assets) is creation of an accurate, as-built data set of the asset geometry or system design. This is the foundational element, over which data is connected and overlaid.

Data is collected through a variety of survey and reality capture techniques (such as point cloud scanning, drones, photogrammetry, drawings/sketches, etc) which are more accurate, efficient and cost-effective than was possible just a few years ago, and significantly more so than traditional survey methods.

Equally, for certain situations or assets a drawing or sketch might be an appropriate method of reality capture.

Element 0 immediately provides value through having greater asset certainty, spatial context and understanding. This is particularly true in sectors where a high proportion of assets are built and ageing, or in high-hazard sectors where it reduces worker exposure to dangerous tasks. Sometimes it's appropriate to work within these point-cloud datasets, but often there is significant value in going to the next level of maturity.

Element 1

2D map/systems or 3D model (object-based only)

Element 1 is the typical entry-point for new assets as an outcome of the design process and is often updated through reality capture (as per Element 0) post-construction to create the as-built model.

Models are purely object-based (surface, shapes, etc), with no metadata or BIM information attached. Point-clouds from Element 0 can be proportionally converted, as and when required, into object-based 2D map/systems or 3D models. The conversion is largely a manual process today but will soon be done through semi-automated methods involving machine learning.

At this level of maturity, the twin provides significant value through design/asset optimisation and coordination, answering questions, such as: is there space to run a new line through that module? And how would the maintenance team conduct that task?

Element 2

Connected to persistent (static) data, metadata and BIM Stage 2

Further benefits are realised when Element 1 is connected to persistent data-sets, such as design information, material specifications, inspection reports, and asset management information; and further enriched with metadata (i.e. BIM). The data is added, tagged and pulled from existing systems, not embedded or stored in the 2D/3D model directly.

This provides the basis for engineering, project planning, operations, maintenance and decommissioning. It creates a single reference point from which all data can be viewed and interrogated, reducing errors, uncertainties and costs. It enables faster decision making and collaboration; answering questions such as: Are we on target with our schedule and budget? Where are the highest risk items?

Having a data model of this maturity also allows integrated multi-physics, multi-scale, probabilistic simulations to be run against the asset, either directly in the twin or through connected simulation applications; answering 'what if' questions such as: If I change X how will it impact Y?

> Adoption of these elements is not necessarily linear or sequential, a twin might possess features of higher order, more complex elements, before lower ones.

Element 3

Enrich with real-time (dynamic) data

Facilitated by sensors, connected devices and the Internet of Things (IoT), dynamic or operational data is obtained and displayed in real (or near-real) time through one-directional flow from the physical to the digital asset. This data can be analysed to inform and predict the behaviour of the built asset, and facilitate decision making, with the output or results fed back and updated into the organisation's existing systems.

This element of maturity is what many technology and service providers would identify as the starting point of a 'true' digital twin, though getting to this level of maturity requires several previous steps that are often not detailed.

Developing Element 3 requires sensors and connected devices to actively or passively capture and collect data. This is often the first significant investment.

Element 4

Two-way integration and interaction

The state and condition of the physical asset can be changed via the twin, with output and results fed back and updated into the twin. For example, an operator could manipulate a physical valve or activate machinery by initiating the action from the twin. This level of integration requires additional sensor and mechanical augmentation of the physical asset.

This integration can also apply between the twin and other digital assets, such as other twins or even engineering systems and applications. For example, a designer using immersive technology modifies the design, the change is pushed to all connected applications, including the engineering design and process simulation package. The connected applications calculate the impact of the change and update the geometry and data accordingly, with these updates and their impact reflected live into the twin for the designer to see.

This full integration demonstrates the two methods of interacting with digital twins; human-to-machine and machine-to-machine.

Element 5

Autonomous operations and maintenance

In the future it's not hard to imagine that the digital twin learns and evolves as a living repository for institutional knowledge, absorbing enough experience about the behaviour of the physical asset that it could become completely autonomous in its operations, able to react to anomalies and upsets and can take the necessary corrective action with little or no human interaction.

Achieving this level of maturity is purely aspirational at present, with only small facets of it for discrete situations possible now. The full ramifications of what Element 5 maturity means, and the quantifiable benefits it will bring, are yet to be fully understood.

3.1. Analytics and simulation engine

Around the digital twin, wherever it sits on the maturity spectrum, is a data analytics and simulation engine. This interrogates the data to surface patterns and relationships, and enables trainable models based on AI and ML methodologies. It also allows simulations to be run against the asset, using any of the data available across the maturity spectrum. For example, simple simulations could be run using just the reality capture data (Element 0); or multi-physics, multi-scale, probabilistic simulations from higher-order elements. These simulations can run either directly in the twin or through connected simulation applications, answering important 'what if' questions such as: If I change X how will it impact Y?

There are many consumers of the data within a twin, each of whom will be securely presented a different view – dependent on their requirements and access permissions – to the constellation or ecosystem of technologies that create this truth.

3.2. Digital ecosystem

Each digital twin will fit into an organisation's overall digital ecosystem like a node in a network, alongside potentially many other twins for different assets or systems. These twins can be 'federated' or connected via securely shared data, and will become an embedded part of the enterprise, as intrinsic in management of the organisation as any other functions such as finance or human resources.

Although organisations strive to achieve the higher-order Elements 3 and 4, the reality is that most are only ready for the Elements 0, 1 and 2. This shouldn't be of concern, as each milestone provides significant incremental value.

It's also possible that higher-order elements are not necessary to achieve the organisation's objectives, and a digital twin should always be created and developed with a specific purpose in mind.

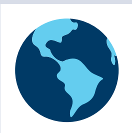
4. Applications in the built environment

There are numerous applications for digital twins in the built environment; however, in this paper we focus on three key applications considered to offer the highest overall benefit. These are: using digital twins for developing smart places, retrofitting existing built assets and resource management.

4.1. Smart places

Current trends of urbanisation suggest that more than 68% of the global population will live in cities by 2050[10]. This increasing concentration in built spaces rather than natural ones means societies need to confront specific challenges. These include shifting to more sustainable resource consumption (especially for food, water and energy) and reducing the environmental degradation causing the destruction, pollution and extinction of species and habitats from which our resources are obtained.

4.1.1 Environment



Global awareness of the emergency described above is at the point where progressive governments are incentivising sustainable built environment design.

The paradigms of consumption and expansion that defined the age of urbanisation and industry are now being displaced by conservation and optimisation. Digital twins can help us more efficiently manage demand in urban places on transport infrastructure, pollution, growing energy consumption and other challenges – especially as these challenges increase. They will be able to articulate the interplay between various systems, for instance how transport and energy are connected, providing a level of understanding that allows planners, designers and operators to make wide-ranging improvements.

As climate change leads to more extreme weather events, engineering can assist the natural world's ability to respond; using the twin as a data collection, analysis and information portal to identify our best options. For example, adapting landscapes by growing trees in an upper catchment areas, or proactively reducing demand for water to reduce the impact of drought.

Using a digital twin as a single version of truth could help create a more circular economy, guiding the reuse of materials. Applied to industries like farming, a twin could help identify patterns to improve operations, optimise maintenance and remotely monitor soil and crop health.

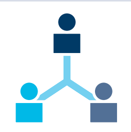
4.1.2 Security

Digital twins can also play a critical role in making urban spaces safer by enabling a multi-faceted, multi-layer view of what's happening – yet be set up for privacy by design.

By focusing on delivering outcomes citizens want, they could help manage security operations, improve resource allocation and inform responses to emergencies. We could use data-sets from twins to train responders and, through drills in AR/VR-driven synthetic environments, improve the efficiency of any number of services, such as remote operations.

To embrace the full value of digital twins it's important to highlight the need for all stakeholders to follow best practice, mitigating the chance of security breaches and availability issues. Twins should be citizen-centric, open and transparent. A digital-centric approach that can help shape outcomes and improve resource management, albeit in a live environment, not track who we all are or where we have been.

4.1.3 Collaboration



From a smart city perspective, digital twins can support the breaking down of institutional and legal silos, unlocking multidisciplinary collaboration.

Using twins at a large scale can allow us, in near real time, to analyse how cities are being used, tracking performance to better manage and operate them.

In practical terms, this could be seen in the coordinated maintenance of underground utilities, by providing information on the impact of road closures on local transport networks, helping contractors align work schedules and keeping citizens aware of service downtime.

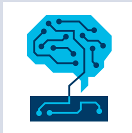
Detailed digital blueprints of our built assets, overlaid with the status of people, systems and incidents, can enhance and support emergency responders by adapting infrastructure to extreme events such as floods. They could automatically re-direct traffic flows, turn road tunnels into storm drains, lower water pressure and supply as needed and offer a real-time status view to residents.

4.1.4 Design

If the whole is to function in an integrated way, then good urban design cannot escape the requirement to understand legacy and lateral systems. To foster good urban design we must gather the information required to understand legacy and new systems, and represent that information in a way that's relevant and accessible to stakeholders through open data.

Contemporary built environment design should reflect an awareness that all the systems within an urbanisation are in parallel. If we take the UK as an example, old cities like Central London and new towns like Milton Keynes face surprisingly similar challenges in terms of congestion and pollution. A new smart transport or supply system might be implemented with step-change improvements to quality of life and sustainability, but if no measures are taken to monitor and integrate with the existing infrastructure, then benefits cannot be quantified or optimised.

4.1.5 Artificial Intelligence (AI)



We have the technology to create systems that monitor and represent our patterns of consumption, to task computers to learn about the urban organism's patterns and preferences, and to give those computers a degree of control over systems where they automatically deliver desired efficiency increases. So what's holding us back?

Public confidence around controlling our cities using AI is yet to be earned. But if we consider AI being applied across multiple systems including transport and power, within an environment occupied by millions of people, it's easy to appreciate how the consequences of errors could be grave. Humans still need to be able to understand why decisions made by AI are happening when they do.

AI has the potential to optimise a circular economy, where resources are not obtained, consumed and disposed of in a linear fashion, but cycled efficiently.

Through such management of resources and by showing their availability, an AI-enabled digital twin could gradually move us away from the concept of ownership towards shared schemes for vehicles, space, storage, tools, clothes and more.

Electric vehicles could be used to store energy and feed it back into local grids as required, with a twin working to provide assurance and confidence to owners that enough energy will still be available for their journeys.

There are a number of existing EU-funded Horizon 2020 projects looking at the food-water-energy nexus. These projects are creating models of how this nexus operates. One such project is CRUNCH[20]. Using Urban Living Labs (ULL's) that are scattered throughout the EU and beyond; the digital twins these ULL's build will try to mimic the flows that occur in a food-water-energy nexus.

This will allow citizens and decision makers to ask `what if' scenarios and track how their activity is impacting the consumption, recycling and re-use of natural resources.

4.2. Retrofitting

Digital twins can support the retrofit of existing built assets.

The UK Government has committed to cutting carbon emissions 80% by 2050[12], but there are currently only a limited number of buildings compliant with the ambitious target. With 80% of the homes we will be living in by 2050 already built, the need for retrofit is clear[13].

Whilst developing mature twins for every building and legacy system would likely be cost-prohibitive, disregarding the benefits of a digital twin approach could make the 2050 targets harder to achieve and put long-term sustainability in jeopardy. The challenge, therefore, is to overcome the barriers of adopting digital twins for existing assets.

In terms of meeting carbon reduction goals, only deep-retrofits (where an asset undergoes a single, complete refit in a defined period of time) can assure achievement of the 2050 target, because only they can be performance tested.

4.2.1 Financing

Retrofit must be funded. One of the most successful models for funding so far has come from the Netherlands. Energiesprong[19], also being piloted in the UK, is a financial model to borrow against later savings on energy bills, repairs and maintenance.

If a digital twin based on collective data was available to better illustrate energy savings, it would encourage lenders to offer potentially more capital to owners and provide them with confidence in the value of the retrofits as an ongoing asset and a saleable commodity.

4.2.3 Confidence

Another critical aspect of success is consumer confidence (most retrofits will be around home-occupants). Digital twins might help to reassure residents and landlords that the disruption and cost of a deep-retrofit can be managed and is worthwhile.

Supported by robust anonymising of personal data, twins can also enable greater understanding of remedial measures at a city-level, allowing local authorities and government to incorporate deep-retrofit planning strategies.

4.2.2 Materials

Material manufacturers and construction companies have been hesitant to commit resources to engage with deep-retrofit at the scale and with the urgency required. The IET white paper Scaling up Retrofit 2050[13] cites a number of contributing factors, including insufficient skills and understanding in the workforce, limited technical solutions, lack of supply chain integration and lack of facilities for pre-fabrication.

A digital twin can enable the flow of information and data, increase collaboration through the supply chain, reducing silos and increase the understanding of existing assets, their current performance, limitations and opportunity for improvement.

Transparency about materials would make it easier for manufacturers to adopt better practice and improve certainty in procurement, tracking of items as they leave one owner before being picked up by another and repurposed. Distributed ledger technology, such as blockchain, could also assist this, proving authenticity of components and circular economy credentials.

A live or near real-time model of where materials are could converge with a smart transport system to negotiate paths to and from construction sites. Providing a green light through-journey for construction traffic would minimise congestion and air pollution, as well as delivering supplies faster and more efficiently. From a revenue perspective, the city could sell "fast paths" to construction sites.

Looking beyond 2050, digital twin data on embedded materials could allow for more sustainable construction from materials re-claimed at demolition, giving the data long-term purpose and value.

4.3. Resource management

As the global population grows and the shift towards urbanisation continues, it becomes imperative to design more sustainable spaces, reduce consumption of resources and minimise environmental degradation.

Once a digital twin is trusted to measure resource usage, it can assist resource owners and managers in making better informed decisions.

This could range from forecasting more accurately and eliminating waste, to proactively managing more nuanced usage thresholds such as measuring air quality, finding zones struggling with poor quality and knowing and controlling behaviours to change that outcome. The twin becomes the trusted data collector, providing understanding of both the current state and the required steps to improve it.

As another example, electric vehicles could be used to store energy and feed it back into local grids as required, with a twin working to provide assurance and confidence to owners that enough energy will still be available for their journeys..

Using a twin to track components in a supply chain will also ensure the re-use, recycling and re-purposing of these components at the end of (their first) life. This type of twin would be open to others, allowing for efficient tracking of 'spares', and creating a realistic capture of how the planet's resources are being used.

To better manage our existing assets, digital twins can assess value, depreciation rate and performance data, enabling informed decisions about asset maintenance and OPEX expenditure, ensuring operation is as efficient as possible. While these types of decisions can be made simply using data analytics, a 3D twin provides visual confirmation and spatial context, making it easier to understand what, where and why work is required.

To appreciate the rationale for embracing and implementing digital twins, their creation must always be associated with measurable benefits. Those benefits will likely touch multiple parties and will facilitate sustainable environmental, operational and economic outcomes.

5. Conclusions

Ultimately, digital twins provide us with an opportunity to improve the environment where we all live and work. Their form and formats are yet to be fully developed, but it's already possible to appreciate the benefits that could be realised.

Thanks to IoT and technological advancements such as LoRaWAN and 5G, the cost of sending data and the volume that can be sent now make it economically and technically viable to create digital twins. Equally, the increase in accessability and the reduction in the cost of storage and computing power allows these volumes of data to be economically stored and analysed.

Having complete knowledge and lifecycle understanding of our assets, including their impact on the natural environment, and being able to visualise them with 3D spatial context, will be priceless. Plus, by connecting multiple digital twins together, we can create powerful perspectives that can tell us how our places, built environment and natural resources are being used and operated. Feeding this information back into the design-build-operate lifecycle allows for the creation of more efficient and better-built assets.

The business case for using a digital twin approach for a sustainable built environment is simple. A twin can act as a central repository of information for stakeholders who do not necessarily call an asset's components or systems the same thing. It can incorporate legacy system information in a form that allows its properties to be usefully amalgamated with new system information. This creates an inherent understanding of the way the built asset has been designed and constructed, the capabilities of all components, and how its constraints interact with each other, the environment and society over time.

Despite this, there are barriers to implementation. In the short-term, these relate to the ownership and secure handling and management of data – especially against the backdrop of high profile data breaches. Long-term we'll need interoperability between digital twins, facilitated through a common language and standards and a robust governance framework.

With the world's urban population forecast to grow by more than 2.5 billion between now and 2050, the design and logistical challenge is immense. Only by embracing and maximising the use of the latest digital technologies and construction methods can we hope to answer it.

5.1 How do we move forward with digital twins?

Embrace the concept now:
All new projects should adopt a digital twin approach, and ensure that the principles are not value-engineered out. For retrofitting to fully succeed, it must also embrace the benefits a twin approach provides.

Respect the journey:
The creation and management of a digital twin is a journey relevant to the entire project lifecycle. We should focus on purpose at each stage, understand the benefits of each milestone and expect value to increase along the journey.

Collaborate:
Overall success will only come through collaboration between government, industry, academia and society. We must all be actively involved in the conversation and push for industry standardisation. We should unify around common organisations, such as CDBB in the UK, and standard definitions and models, such as the maturity spectrum (see page 10).

Regulate:
Governments must take the lead and drive national policy to create shared frameworks and ecosystems.

Get out of silos:
Although this paper focuses on application in the built environment, digital twins transcend sectors. We must learn from each other and contribute to a common good, working collectively to meet global challenges.

Be sustainable:
Adopting a digital twin approach now will enable society to make the necessary shift to more sustainable operations, making us better equipped to meet the UN Sustainable Development Goals (SDGs)[10].

6. References and acknowledgements

1 National Infrastructure Commission, *Data for the public good*, 2017.
2 Centre of Digital Built Britain, *The Gemini Principles*, 2018.
3 MarketsandMarkets, *Digital Twin Market | Industry Analysis and Market Forecast to 2025*, 2019.
4 Gartner, *Prepare for the Impact of Digital Twins*, 2017. [Online]. Available: www.gartner.com/smarterwithgartner/prepare-for-the-impact-of-digital-twins; [Accessed: 02-Sep-2019].
5 M. M. Herterich, *Exploring how digitized products enable industrial service innovation*, in ECIS 2016 Proceedings, 2017, vol. 10243 LNCS, pp. 1–17.
6 B. Marr, *What Is Digital Twin Technology - And Why Is It So Important?*, Forbes.com, March 2017.
7 M. Grieves, *Digital Twin: Manufacturing Excellence through Virtual Factory Replication* 2015.
8 ODI, *Can data trusts increase or help data sharing?* 2019. [Online]. Available: https://theodi.org/project/data-trusts. [Accessed: 09-Sep-2019].
9 Vanzi, *Digital Built Australia*. [Online]. Available: www.vanzi.com.au [Accessed: 16-Sep-2019].
10 UNDESA, *Revision of the World Urbanization Prospect report*, 2018.
11 S. Evans, *Beyond buzzwords: the true meaning and value of 'digital twins'*, 2019. [Online]. Available: www.snclavalin.com/en/beyond-engineering/beyond-buzzwords-the-true-meaning-and-value-of-digital-twins [Accessed: 02-Sep-2019].
12 BEIS (UK Government), *UK becomes first major economy to pass net zero emissions law*, 2019.
13 The Institute of Engineering and Technology & Nottingham Trent University, *Scaling Up Retrofit 2050*, 2018.
14 Techopedia, *What is Fourth Normal Form (4NF)?* 2016. [Online]. Available: www.techopedia.com/definition/28325/fifth-generation-wireless-5g [Accessed: 06-Sep-2019].
15 Techopedia, *What is Artificial Intelligence (AI)?* 2018.
16 BIM Initiative, *BIM dictionary*. 2014.
17 National Building Specification (NBS), *What is BIM?* 2018.
18 Designing Buildings Wiki, *Built environment*, 2018. [Online]. Available: www.designingbuildings.co.uk/wiki/Built_environment [Accessed: 05-Sep-2019].
19 Energiesprong, *Energiesprong explained* [Online]. Available: www.energiesprong.org [Accessed: 16-Sep-2019].
20 CRUNCH, *The Food-Water-Energy Nexus*, [Online]. Available: www.fwe-nexus.eu [Accessed: 01-Oct-2019].

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7. Glossary of terminology and terms

5G:
Fifth generation wireless (5G) is a wireless networking architecture that aims to increase data communication speeds by up to three times compared to its predecessor, 4G. 5G is primarily designed to enable a superior data communication rate between wireless local area networks (WLAN)[14].

Artificial Intelligence (AI):
Artificial intelligence is a branch of computer science that aims to create intelligent machines. It has become an essential part of the technology industry[15].

Asset Management Systems:
An organisational system to manage asset data and related information. An asset management system may refer to a digital platform or a set of internal processes/protocols[16].

Building Information Modelling (BIM):
A process for creating and managing information on a construction project across the project lifecycle. One of the key outputs of this process is the building information model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project[17].

Building Lifecycle Management (BLM):
The adaptation of PLM-like techniques to the design, construction, and management of buildings. Building lifecycle management requires accurate and extensive BIM. Lifecycle management of the built environment requires a standardised ontology and the integration of disparate competencies, technologies, and processes.

Built Environment:
The term 'built environment' refers to aspects of our surroundings that are built by humans, that is, distinguished from the natural environment. It includes not only buildings, but the human-made spaces between buildings, such as parks, and the infrastructure that supports human activity such as transportation networks, utilities networks, flood defences and telecommunications[18].

All forms of buildings (residential, industrial, commercial, hospitals, schools), all economic infrastructure (above and below ground) and the urban space and landscape between and around buildings and infrastructure are part of the built environment[2].

Computer-Aided Design (CAD):
Refers to the use of digital tools generate, modify, analyse, or optimise an object or a space. CAD represents all pre-BIM digital tools and their 2D/3D deliverables[16].

Common Data Environment (CDE):
A single source of information which collects, manages and disseminates relevant, approved project documents for multidisciplinary teams in a managed process. A Common Data Environment (CDE) is typically served by a Document Management System that facilitates the sharing of data/information among project participants[16].

Digital twin:
A realistic digital representation of assets, processes or systems in the built or natural environment. What distinguishes a digital twin from any other digital model or replica is its connection to its physical twin[2].

Digital twin maturity spectrum:
An industry-agnostic spectrum, developed by Simon Evans at Atkins. The digital twin maturity spectrum was created to help define the elements and requirements of a digital twin and provide a framework for communicating the complex concept. The spectrum presents six identifiable elements that are not necessarily linear or sequential in occurrence but increase logarithmically in terms of complexity and connectedness[11].

Internet of Things (IoT):
Refers to the connection of devices, other than typical fare such as computers and smartphones, to the Internet.

National Digital Twin (NDT):
For infrastructure – an ecosystem of digital twins connected via securely shared data – represents an exciting future vision for civil engineering, as we strive to better serve the needs of people and businesses[2].

Product Lifecycle Management (PLM):
Refers to the handling of a good as it moves through the typical stages of its product life: development and introduction, growth, maturity/stability, and decline. This handling involves both the manufacturing of the good and the marketing of it. The concept of product lifecycle helps inform business decision-making, from pricing and promotion to expansion or cost-cutting.

8. Authors

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Simon is Director of Digital Engineering for Atkins and the SNC-Lavalin Group, where he's part of the leadership team responsible for the global transformation of the +$5bn consultancy and construction group.

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The Institution of Engineering and Technology

The Built Environment Panel of the Institution of Engineering and Technology (IET), has identified a growing interest in digital twins: what they are and what they can do, as well as a lack of clarity around their benefits and opportunities in the built environment.

The objective of this paper is to provide a clear, consolidated explanation of the digital twin and its applications. This is paired with an industry-agnostic digital twin maturity spectrum from Atkins', which defines the elements and requirements of the twin and provides a framework for communicating the complex concept.

This paper intentionally does not address some of the more advanced questions about the technology or international progress in adoption. Some of these will be addressed in later works.

To see further examples of the Built Environment Panel please visit theiet.org/built-environment

For more information on the authors of this paper, see page 23.

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