ARUP

Digital twin

TOWARDS A MEANINGFUL FRAMEWORK

About Digital

Arup is committed to shaping the digital built environment. Our clients look to us to combine deep domain knowledge and new technologies with strategies that sharpen performance, uncover new business models, and ensure that they thrive in this new, connected world. We seek collaborations with research partners in our mission to shape a better world.

About Foresight, Research and Innovation

Foresight, Research and Innovation is Arup's internal think-tank and consultancy which focuses on the future of the built environment and society at large. We help organisations understand trends, explore new ideas and radically rethink the future of their businesses. Research has played a fundamental role in defining how we anticipate and leverage emerging business opportunities. Applied research continues to underpin our ability to address our clients' greatest challenges.

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Download the report at www.arup.com/digitaltwinreport

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FOREWORD

To fulfil its potential, the concept of digital twin(s) has to evolve into a real and meaningful construct and not just another idea on the never-ending digital hype cycle.

A digital twin, as a means to link digital models and simulations with real-world data, creates new possibilities for improved creativity, competitive advantage and human-centred design. Digital twins can help deliver on the grand challenges facing society, including achieving the United Nations' Sustainable Development Goals and addressing rapid urbanisation, population growth, and escalating infrastructure costs.

In their current state, digital twins can improve our designs and the advice we give to our clients, yet challenges remain. Sharing data comes at a high cost and with great tension, as digital knowledge, practices and culture are not yet converging across the built environment. To realise the full value of our work, we must develop partnerships through deep understanding and greater collaboration around a meaningful approach: an inspiring vision supported by clear actions.

In this report, we present the current state of digital twins in the built environment and explore ideas on what might become possible in the future. The research examines a broad spectrum of digital twins, both in use and in development, and finds varying levels of progress and investment in early prototypes, practice and governance. We hope that this research can inform and influence, so that we carefully consider the purpose of digital twins, human factors, integrity and security. There is a clear need to collaboratively define and lead the development of a digital twin narrative that works across the built environment.

This report was developed through collaboration with global experts and their use cases, and we are grateful for their ideas and contributions. Our research included both enthusiasts and critics in our aim to explore how we can best combine human and machine intelligence, creativity, and technologies into digital twins that can help our mission to shape a better world.

Our aim in sharing this work is to bring the industry together into an important journey. A journey towards meaningful developments of digital twins, which drive value for our clients and society as a whole. As we continue to explore and collaborate, we encourage you to stay in touch with us via digital@arup.com. We welcome your feedback and interest in creating digital twins of today and for the future. ■

VOLKER BUSCHER
Chief Data Officer
Arup

CHAPTER 1

Current state of digital twins

Will digital twins be the technology that can help tackle climate change, radically modernise water and transport infrastructure, and help us achieve the United Nations' Sustainable Development Goals?

INTRODUCTION

The digital twin concept offers great potential value for organisations in the built environment. The widespread use of digital twins holds the promise to increase operational efficiency, allow for resource optimisation, improve asset management, deliver cost savings, improve productivity and safety. The digitisation of the built environment, enabled by an increase in computing power, cheaper sensors, Internet of Things (IoT), advanced analytics and greater sophistication of 3D visualisation and immersive environments, therefore has the potential to actively contribute towards achieving the UN Sustainable Development Goals (SDGs).

Yet, while digital twins are clearly in vogue, we have yet to define the extent to which they can drive value for our clients. Digital twins have the potential to disrupt markets, and once we address the barriers of data exchanges, governance, and interoperability, we expect the results to be profound. However, the industry is currently burdened by competing definitions, misunderstandings, and confusion around what a digital twin is and what it can do. The aim of this report is to align terminology, and to provide a working evaluation framework to clearly categorise the various levels of sophistication of digital twins.

The report was informed by interviews with 75 experts from across the industry, including thought leaders within key markets; cities, energy, property, transport and water. The report includes exemplary case studies of emerging uses of digital twins in the built environment, which are evaluated using our working framework.

CURRENT STATE OF DIGITAL TWINS

The digital twin is becoming a widely familiar concept. In 2003, Michael Grieves coined the term ‘digital twin’ as part of his research into product lifecycle management.[1] On page 24, Dr Grieves sheds light on the evolution of digital twins for the built environment. General Electric, Siemens and Rolls Royce were designing rotors, turbines and engines with the aid of simulations decades before the term was coined. Similarly, the oil and gas industries have been working with simulations of fuel reservoirs since the 1980s. Prior to Grieves’ coinage, industry used terms as diverse as ‘digital shadows’, ‘digital avatars’ and ‘digital models’. As we look at the history of the digital twin, we must make an important distinction between a digital model, a simulation and a digital twin. A digital twin is not a static model but rather, a responsive system connected between the physical and digital systems. In the following paragraphs, we provide examples of how the industry is thinking and adopting digital twins across the industry.

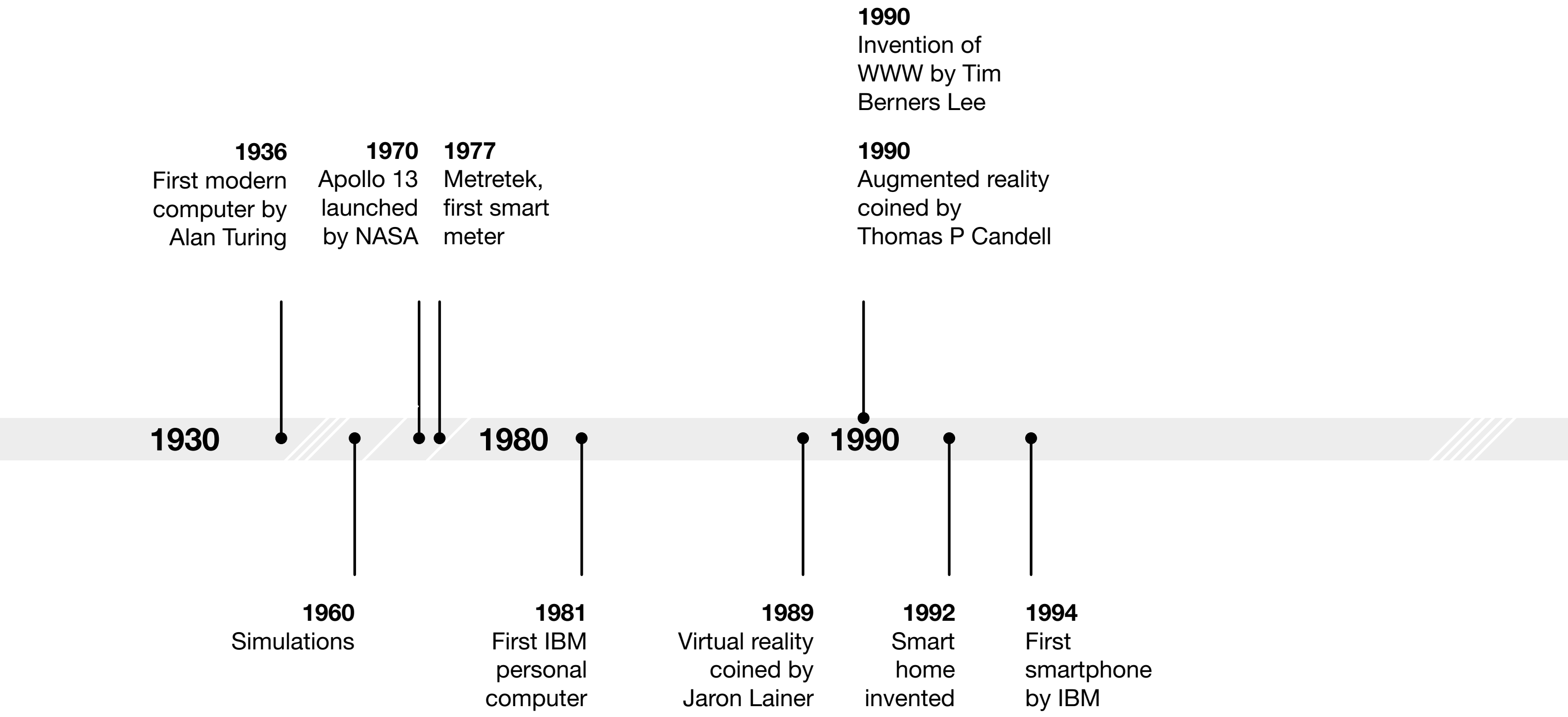
At DHL, an international courier service, the employment of digital twins is underway, and the firm is exploring the challenges and opportunities of integrating them into their core operations.[2] In automotive manufacturing, Siemens is creating digital twin products to enable realistic simulations to optimise a car before it has been built.[3] Meanwhile, software companies such as SAP and Microsoft are promoting the use of machine learning and IoT to help companies optimise their operations.[4,5] IBM Watson, on the other hand, are providing services towards product lifecycle improvements, and creating deeper insights between design and operations.[6] ▶

The software industry is creating products to integrate, analyse and manage high-throughput data, targeted at smart cities, product manufacturing and asset management. At the city scale, the Smart City Digital Twin paradigm has been introduced to increase the transparency of human-infrastructure-technology interactions through the exchange of spatiotemporal information.[7] At the national scale, the British government is looking into model federation and data sharing.[8] Recent advances in artificial intelligence (AI) have enabled better insight and analysis of physical assets, yielding a rich dataset of previously inaccessible information. Advanced digital twins can be found in the property and transportation markets, with some of the most prominent examples coming from tech giants like Google.

As a first, small-scale example, we can take the Google Nest learning thermostat. This device, when paired with heating systems, has the ability to programme itself by switching the system on and off or choosing between heating and air conditioning based on the temperature it detects in the room. The Nest learns behaviour by understanding the patterns and desired temperatures for certain days and times during the week, and then creates a schedule for heating, ventilation and air conditioning (HVAC). It is the first thermostat on the market to incorporate a learning element, making decisions on behalf of its users with the aim of providing a more comfortable environment.[9] A larger-scale example comes from Google DeepMind, who trained AI systems to manage the cooling of their data centres. The system uses reinforcement learning, determining by trial and error which cooling configurations consume the lowest amounts of energy. The system was able to consistently achieve a 40% reduction in energy used for cooling, which equalled a 15% reduction in overall power usage.[10]

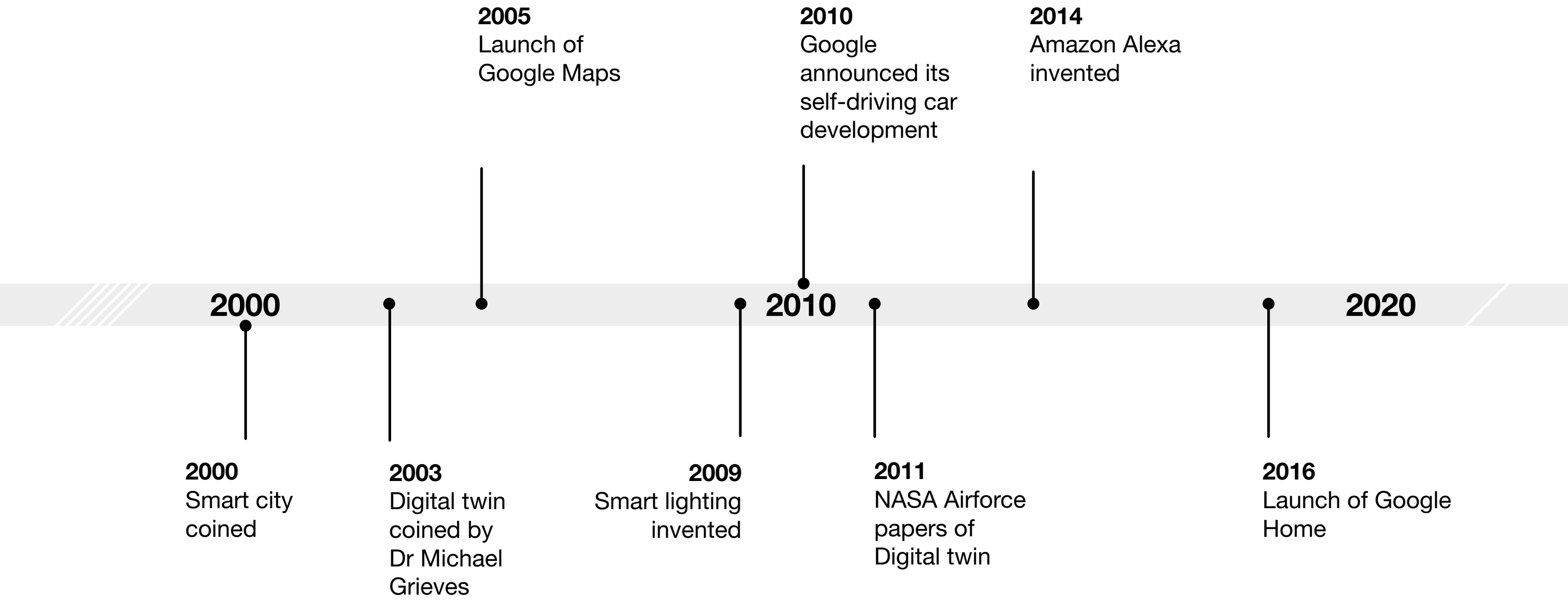
Self-driving technology is one of the most advanced examples of applied AI twin in society today, with an important aim of reducing accidents caused by human error. Consortium partners such as the UK Autodrive programme are collaborating to advance this technology.[11] Google Maps is another good example.[12] While it may have drawbacks such as it is not always 100% accurate and requires constant updating, the maps is still best characterised as an advanced digital twin, providing a relevant representation of the built environment and real-time information. The Google Maps API is now an essential substrate for many services such as ridesharing, restaurant reviews and business information, resulting in a comprehensive and unified platform of great value. ►

FIGURE 1
Below
Digital twins emerging technology timeline



At the city scale, the ambitious plan of Sidewalk Labs to build a state-of-the-art 'responsive neighbourhood' is projected to draw £29.5b of private sector investment by 2040.[13] The project is aiming to reimagine cities and improve quality of life. Among other things, the project will create a digital twin of a section of Toronto's waterfront by modelling and collecting data from a network of sensors in public spaces. In addition, the project is developing an underground freight delivery system and tracking the delivery of packages, to avoid clogging the streets with trucks.

Lastly, consider Uber's on-demand transportation service, which uses a machine learning platform, Michelangelo. This platform is a digital twin of Uber's entire network that connects drivers and users based on supply and demand.[14] The success of the platform has now been expanded to include other services such as Uber Eats (an online food ordering and delivery platform) and Marketplace Forecasting (a spatiotemporal forecasting model able to predict rider demand and driver availability).[15,16] These are all examples of technological advances bringing together the physical and digital worlds. They illustrate the state-of-the-art in hybrid digital-physical systems with high fidelity, increasing autonomy, and adaptability to changing environmental and operational conditions. Given the advances we have seen in other markets, we believe the built environment is ready to embrace digital twins, with new collaborations and partnerships in order to create new opportunities and value propositions.



This report presents case studies from a broad spectrum of digital twin applications. They range from existing, fully functional twins, such as those intelligently optimising the use of office space (as highlighted in the Property market), to more future-oriented projects (such as the Digital Patient case study on Page 62). Healthcare is forecasted to be a fast-moving market, with a new focus on personalised patient care and designs to provide better services to patients including rethinking space and waiting areas within hospitals.[17] Progress made and lessons learned in the redesign of healthcare facilities will be instructive for the built environment.

The purposes and intentions behind the deployment of digital twins found in this report vary across industries and use cases; there is no one-size-fits-all for digital twins. The technological trends enabling their development, and the societal needs calling for this development, can help us define a clear role for digital twins beyond the current hype cycle. In the following section, we present the various definitions of digital twins across the industry and present the digital twin and its ecosystem around better decision making, learning and autonomy. ▶

DEFINITIONS OF THE DIGITAL TWIN

A key motivation for our work has been to help the industry compare the various definitions of digital twins that includes the promises and value yet to be achieved. Table 1 lays out existing definitions of the digital twin from key players in academia and industry. Differences in the characterisations of digital twins are relatively minor, and tend to differ in focus (for example, the entity twinned as an 'object', a 'product', a 'process', a 'system' or some mixture of these). While the characteristics are relatively consistent, the stated purposes of digital twins can vary widely. What is perceived as the main purpose is likely to vary depending on the interests of the researcher or business involved, from increasing return on investment (Deloitte) to ensuring safety (NASA).

Digital twins at first may appear to be an exact replica, however, digital twins are not necessarily *realistic* representations, but are rather *relevant* abstractions of the physical asset. It is not necessary for even the most advanced smart city to digitally replicate the fluting of every column or the mortar of every brick. In other words, we need to develop digital twins that are fit for purpose, and the level of fidelity will vary depending on the primary use cases. Digital twins need not attempt to mirror everything about the original system.[18]

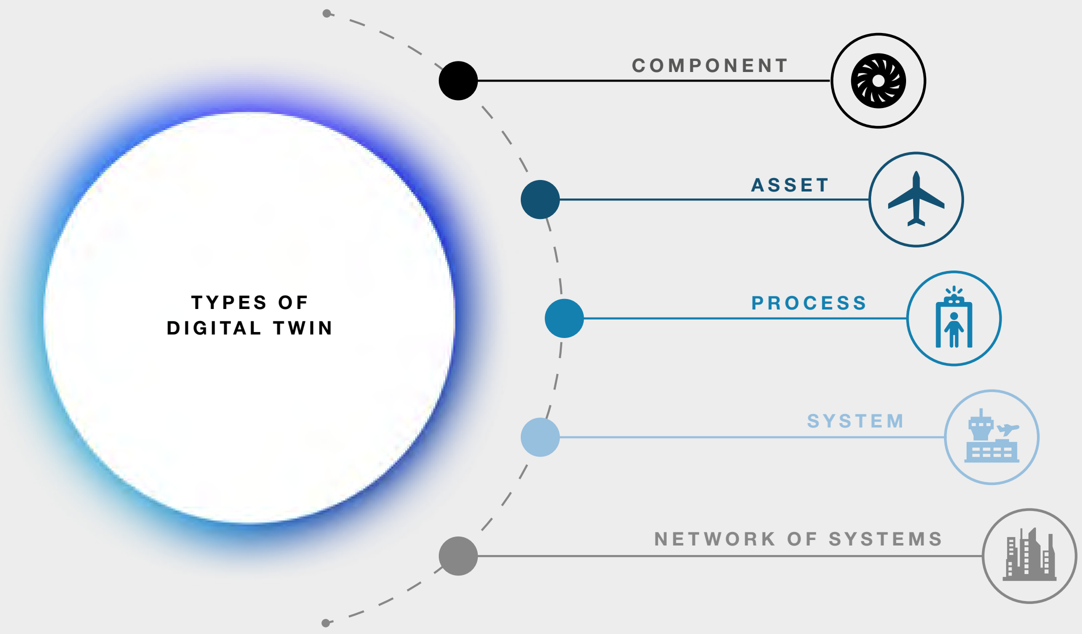
We can make the broad definitional consensus more precise by stating what a digital twin is not. Neither a Building Information Model (BIM), for example, nor a simulation operating in isolation from a physical asset can be termed a digital twin. Rather, there must be a connection between the physical and the digital systems. This requires data exchange, as well as the inclusion of humans in the role of designers or occupants. Digital twins must make ever-improving predictions about our physical infrastructure; in their more advanced instantiations, at least, they will be increasing in intelligence continuously. Overall, the missing idea across definitions, and which we stress in this report, is that the twin controls and optimises the physical asset. In other words, existing definitions shy away from recognising the key role of AI.

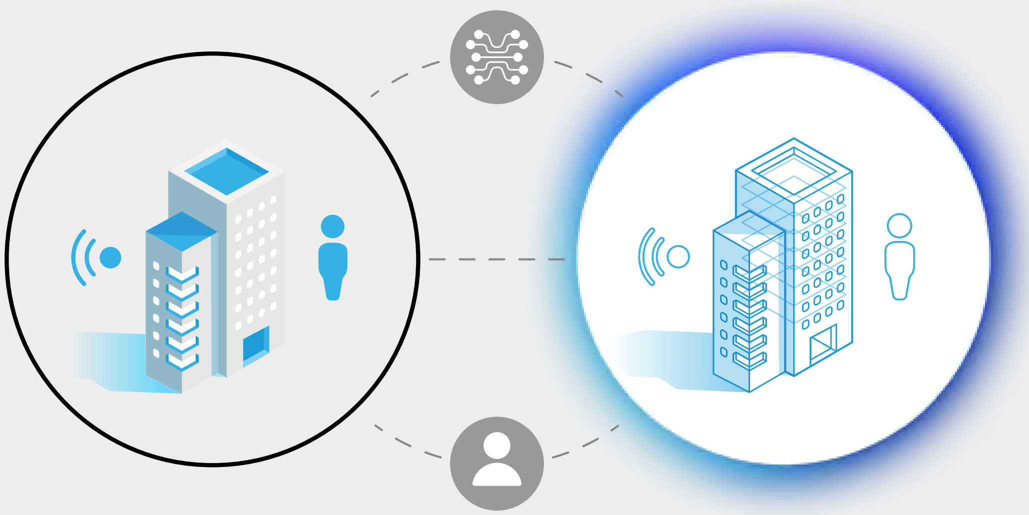
A digital twin is the combination of a computational model and a real-world system, designed to monitor, control and optimise its functionality. Through data and feedback, both simulated and real, a digital twin can develop capacities for autonomy and to learn from and reason about its environment.

As the technology matures, so does the terminology, hence the need to include autonomy, learning and reasoning within the definition. The proposed definition acknowledges that the digital twin is still a model, but it has the potential to evolve into an autonomous system with less human intervention, through AI-enabled design and control. Among the competing definitions, we agree with IBM's definition and the ability for the digital twin to "understand, learn and reason". Over time, a digital twin will not only *lead* to better decision making, but it will *make* better decisions. In the following section, we discuss various types of digital twins and their ecosystems. ▶

TABLE 1
Opposite right
Definitions of 'digital twins' across the industry and academia

SOURCE	DEFINITION
CAMBRIDGE CENTRE FOR DIGITAL BUILT BRITAIN *Academia*	A digital twin is a realistic digital representation of something physical.[19]
DASSAULT SYSTÈMES *Software*	A “Virtual Twin” is a virtual representation of what has been produced. We can compare a Virtual Twin to its engineering design to better understand what was produced versus what was designed, tightening the loop between design and execution.[20]
DELOITTE *Consulting*	A digital twin is a near-real-time digital image of a physical object or process that helps optimise business performance.[21]
GARTNER *IT*	A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organisation, person or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant or a city, and their related processes.[22]
GENERAL ELECTRIC *Conglomerate*	A digital twin is a living model that drives a business outcome.[23]
IBM *Software*	A digital twin is a virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning.[24]
MICHAEL BATTY *Academia*	A digital twin is a mirror image of a physical process that is articulated alongside the process in question, usually matching exactly the operation of the physical process which takes place in real-time.[18]
MICHAEL GRIEVES *Academia*	The digital twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro (atomic level) to the macro (geometrical level). At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin.[25]
MICROSOFT *Software*	A digital twin is a virtual model of a process, product, production asset or service. Sensor-enabled and IoT-connected machines and devices, combined with machine learning and advanced analytics, can be used to view the device’s state in real-time. When combined with both 2D and 3D design information, a digital twin can visualise the physical world and provide a method to simulate electronic, mechanical, and combined system outcomes.[26]
NASA *Government / Research*	A digital twin integrates ultra-high fidelity simulation with the vehicle’s on-board integrated vehicle health management system, maintenance history and all available historical and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability.[27]
SIEMENS *Conglomerate*	A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart’s performance characteristics.[3]





PHYSICAL WORLD
A real-world asset and its behaviour.

DIGITAL TWIN
A digital twin is the combination of a computational model and a real-world system.

USER
The user interacting with the digital twin.

INTELLIGENCE
AI enabling the digital twin to perform tasks with minimal or no human oversight, e.g. visual perception, speech recognition, natural language translation, decision making.

DIGITAL THREAD
Refers to information channels connecting the physical and the digital asset.

THE DIGITAL TWIN AND ITS ECOSYSTEM

The digital twin and its ecosystem may vary in scale and complexity with respect to size and scope. Size is the granularity of the representation (how accurate it is, spatial and temporal scale, for example), and scope is the portion of the real-world that the model considers (i.e. an engine or a city). Digital twins in the built environment range from basic to complex, and are organised into five types as shown in Figure 2. The digital twin can have single or multiple stakeholders, and may make use of 3D simulations, IoT devices, 4G and 5G networks, blockchain, edge computing, cloud computing, and artificial intelligence. Depending on its complexity, each digital twin may have access to past, present and future operational data and increased predictive capabilities. A digital twin can be viewed as a system within an ecosystem. For example, in Figure 3, the ecosystem depicts both a physical asset and its digital twin. The user interacts with the digital twin through applied intelligence while the digital thread connects the physical and digital worlds.

A particularly important function of digital twins is their ability to understand, learn and provide value using a systems approach. For example, a digital twin of an electrical network must simulate the core behaviour of the network — generation, storage and consumption — together with human inputs to the system, as well as the capacity to deal with unexpected occurrences. Only the simultaneous processing of these various kinds of data will enable efficient control of the network. Over time, the digital twin would improve its knowledge of and control over the electricity network, from predictive maintenance to the autonomous suggestion of network improvements and even large-scale redesigns.

As we noted above, any digital twin is modelled at some level of relevant abstraction from its physical counterpart, geared to a specific purpose. This can be viewed as intentionally relinquished information, to streamline a digital twin to its bare necessities. However, we must also be aware of unintentionally relinquished information: we will always be limited by some level of measurement error, and almost always by some level of human error. It is important to limit both of these sources of error to non-intrusive levels.

With further research and development of digital twins, we expect to overcome many of these challenges and provide our clients with a solution fit for purpose. In the following section, we present a working evaluation framework which aims to establish a common language around what a digital is, what it can do and what it can become. ■

FIGURE 2
Opposite top
Types of digital twin

FIGURE 3
Opposite bottom
Digital twin ecosystem

Towards an evaluation framework

We put forward a framework to articulate what a digital twin is, what it can do, and what it can become. Our framework intends to facilitate wider collaboration and discussion of digital twins across the industry.

The objective of the framework is to evaluate the current state of digital twins across five key levels. The levels help the industry to use common language when describing a digital twin and its capabilities. The aim of the framework is to enable participation from our clients and collaborators at all stages of the development. In Figure 4 we present the evaluation framework. The metrics of the framework can be found in Table 2. The four metrics are: autonomy, intelligence, learning, and fidelity. While these four metrics are conceptually correlated, they should be treated independently; as the framework evolves and our understanding of digital twins grows, we can revise the framework and metrics accordingly.

In Table 3, the framework moves through five levels, beginning with a simple digital model. As the model evolves, feedback and prediction increase in importance. At higher levels, machine learning capacity, domain-generality and scaling potential all come into play. By the highest levels, the twin is able to reason and act autonomously, and to operate at a network scale (incorporating lower-level twins, for example). Our vision for the built environment is to work collaboratively towards the development and adoption of 'level 5' digital twins.

Our research has revealed that the progression and development of digital twins is far from reaching level 4 or 5. We are still a long way from an industry landscape populated by reasoning models, machine consciousness, and full autonomy. As digital twins evolve, however, they will control more and more operations, increasing autonomy, intelligence, learning, and fidelity providing value against a backdrop of minimal human intervention.

While we considered other metrics that may be applicable such as maturity, we chose not to include it as a key metric. Maturity refers to the developmental stage of the digital twin, rather than its level of complexity.[28] The stages of maturity run from the initial concept, through demonstration and development, and finally to commercialisation. Digital twins can be highly intelligent and highly autonomous, but nevertheless yet to attain maturity. Therefore, maturity was excluded as a key metric.

In the following chapter, we apply the evaluation framework using the key metrics through a series of Arup case studies to demonstrate how it is applicable across digital twin projects.

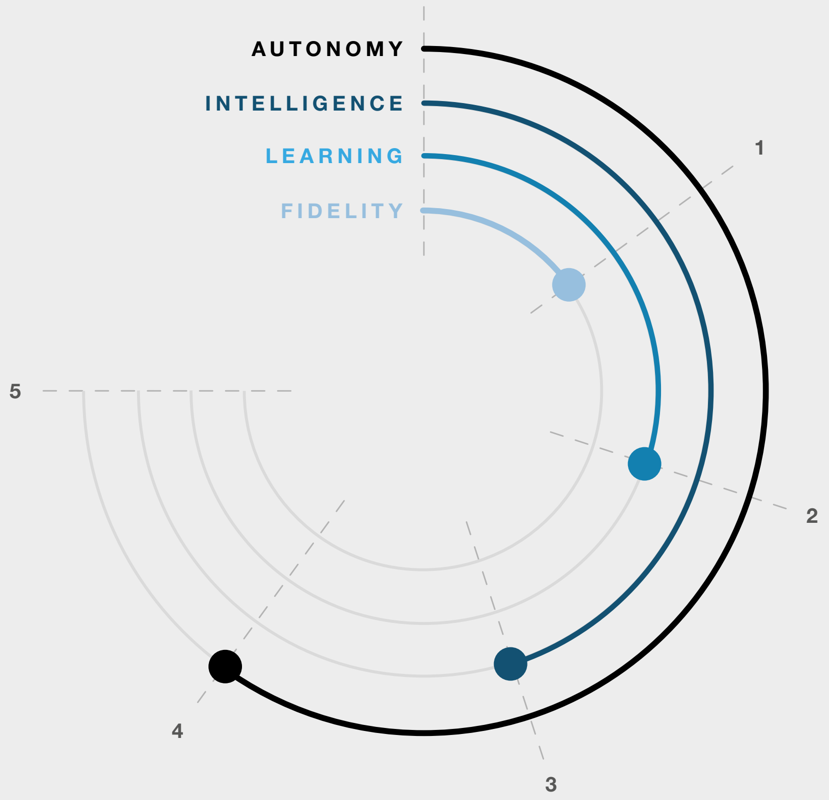


FIGURE 4
Left
Arup's digital twins metrics framework, in terms of their autonomy, intelligence, learning and fidelity

TABLE 2
Opposite right
Working levels of digital twins

TABLE 3
Below
Definitions of digital twin metrics

METRIC	DEFINITION
Autonomy	The ability of a system to act without human input. There are five levels of autonomy. At level 1, there is complete absence of autonomy, with the user controlling all aspects of the digital twin. A level 2 can be understood as user-assisted. At this level, prompts and notifications of system activity are expected, but autonomy is limited. A level 3 has partial autonomy, the twin has the ability to alert and to control the system in certain ways. A level 4 has high autonomy, the digital twin is able to perform critical tasks and to monitor conditions with little to no human intervention. Finally, a level 5 can operate safely in the total absence of human intervention.
Intelligence	The ability of digital twins to replicate human cognitive processes and to perform tasks. There are five levels of intelligence. At level 1, the twin has no intelligence. At level 2, the twin has reactive intelligence (the twin only responds to stimuli, cannot use previously gained experiences to inform their present actions). At level 3, the twin uses learning to improve its response and are also capable of learning from historical data to make decisions. At level 4, the twin understands the needs of other intelligent systems. Finally, at level 5, the twin is self-aware with human-like intelligence and self-awareness.
Learning	The ability of a twin to automatically learn from data in order to improve performance without being explicitly programmed to do so. Through machine learning, a twin classifies aspects of the systems (objects, behaviours) using reinforced learning. There are five levels of learning. At level 1, the twin has no learning component. At level 2, the twin is programmed using a long list of commands. At level 3, the twin is trained using a supervised learning approach (using labelled data able to provide feedback and prediction performance). At level 4, the twin is trained using an unsupervised learning (the twin uses no labels and tries to make sense of the environment on its own). At level 5, the twin uses reinforcement learning by interacting with its environment. With reinforcement learning, the twin learns from past feedback and experiences to find the optimal way to improve performance; the twin uses a reward system for good performance.
Fidelity	The level of detail of a system, the degree to which measurements, calculations, or specifications approach the true value or desired standard. There are five levels of fidelity. At level 1, the twin has low accuracy and can be considered as a conceptual model. At level 2, the twin has a low to medium range of accuracy and can be used to extract measurements. At level 3, the twin has a medium range of accuracy and can be used as a reliable representation of the physical world. At level 4, the twin can provide precise measurements and at level 5, the twin has a high degree of accuracy and can be used in the case of life safety and critical operational decisions. Fidelity, therefore, depends crucially on the requirements of a given asset operator, rather than constituting an absolute property of a digital twin.

LEVEL 1

A digital model linked to the real-world system but lacking intelligence, learning or autonomy; limited functionality e.g. a basic model of a map.

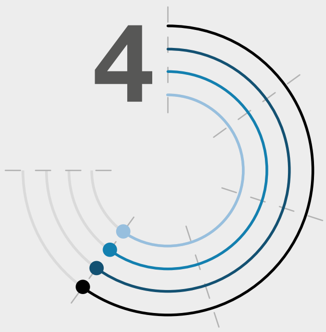
LEVEL 2

A digital model with some capacity for feedback and control, often limited to the modelling of small-scale systems e.g. building temperature sensors which feed information back to a human operator.

LEVEL 3

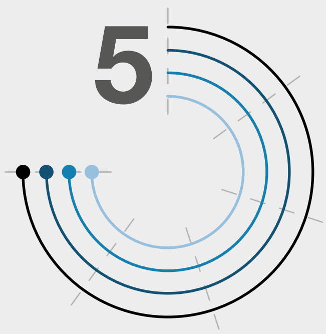
A digital model able to provide predictive maintenance, analytics and insights e.g. predicting the life expectancy of rail infrastructure, enabling repairs or replacements before asset failure.

LEVEL 4



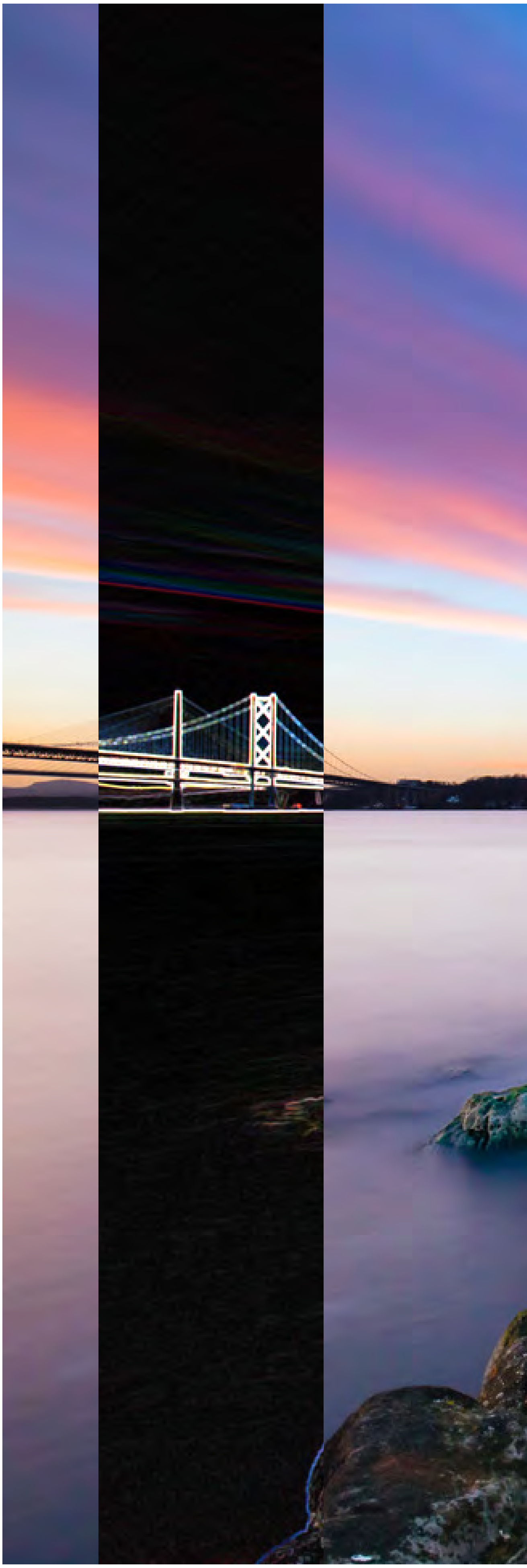
A digital model with the capacity to learn efficiently from various sources of data, including the surrounding environment. The model will have the ability to use that learning for autonomous decision making within a given domain e.g. the model can automatically communicate real-time route recommendations through various modalities (app, signage, radio), allowing drivers to better plan their journey.

LEVEL 5



A digital model with a wider range of capacities and responsibilities, ultimately approaching the ability to autonomously reason and to act on behalf of users (artificial general intelligence). Intuitively, a level 5 model, such as a model of a neighbourhood in a smart city, would take responsibility for the tasks one would presently expect a human operator to manage, as well as to react to previously unseen scenarios. Another hallmark of this level would be the interconnected incorporation of lower-level twins e.g. take the level 4 example of traffic updates across a network. In a smart city scenario, numerous independent systems work in parallel to provide feedback to a central decision making network to deliver value to city-level leaders.

The digital twin concept, from its origin over a decade ago to today, has always relied on progress in two very different areas: technology and culture.



DR MICHAEL GRIEVES
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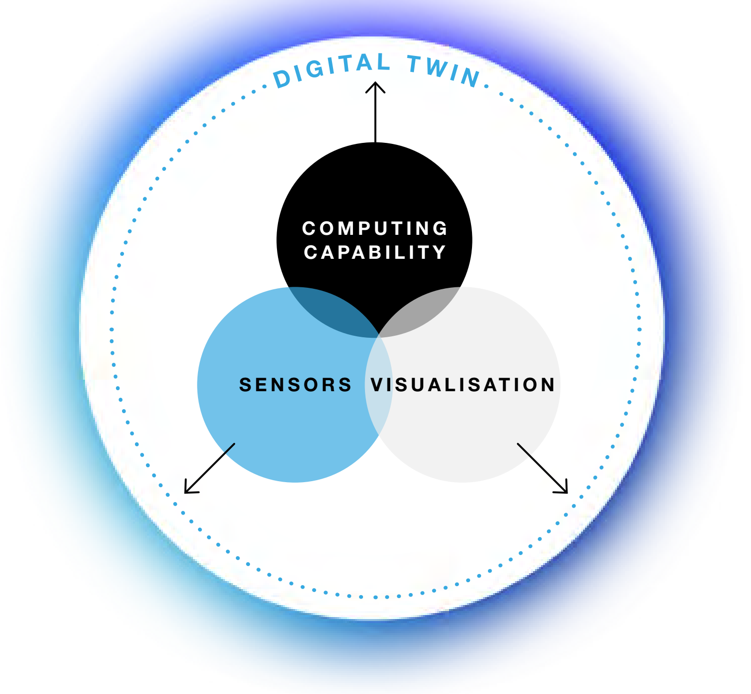
Advances in modeling and simulation allow us to see into the future. We can predict traffic patterns, energy usage, building stresses, fire risks, and other resource and risk profiles. We can move a step ahead in solving issues before they occur.

Ever since the crystallisation of the digital twin concept at the beginning of the twenty-first century, I have always thought that architecture and buildings — throughout their lives — presented a natural use case for the digital twin. The architecture of buildings, with their dynamic visual elements, has evolved rapidly from ideas into 2D sketches and through to 3D physical models. This has given architects an improved sense of how their designs will be physically realised.

Previously, once the design was complete, building designs were translated into fragmented 2D blueprints to inform both the construction and maintenance of the building. This resulted in wasted resources, as information had to be translated from 2D to 3D. There was further waste in the building operation and maintenance phase, since much of the infrastructure was now hidden behind opaque walls and barriers.

This issue is especially pertinent to the urban buildings of today, which operate within complex systems. Modern buildings must integrate a wide variety of subsystems, such as heating, ventilation and air conditioning (HVAC), energy and electrical systems, plumbing and water movement, and ▶



complex elevator systems. These all make modern buildings a fruitful area for the employment of digital twins.

The ability to realise digital twins, from their conceptual origin over a decade ago to where they are today, has always relied on two very different kinds of progress: technological and cultural.

ADVANCEMENTS IN TECHNOLOGY ENABLE DIGITAL TWINS

On the technology front, there are three major advancements that have enabled the digital twin; namely computing capability, sensors, and visualisation.

Digital twins rely on massive amounts of data collection and information processing by historical standards. During the past decade, as computing power has more than doubled ever eighteen months (Moore's Law), we have moved from dealing with the low-end gigabit scale (10^9) up to petabits (10^{15}), exabits (10^{18}), and will soon transcend these by further orders of magnitude.[29]

While Moore's Law deals only with computing capacity, other advancements have occurred in storage and communications bandwidth. This has afforded us the ability to process, store, and communicate the massive amounts of information used to operate modern buildings in previously impossible ways. The second technological advancement has come through sensors, which have enabled the rise of smart buildings. Buildings can now be made to sense and communicate their exact status to allow us to know and manipulate exactly what is occurring within, simply by interrogating their digital twin. We can, for instance, dictate temperature throughout the building, minimise energy use in unoccupied areas, keep tabs on structural stress levels, and adjust lighting on demand. We can predict elevator failures and automate maintenance schedules by aggregating information from different buildings across time. In short, we can predict future performance, and thus pre-empt and eliminate issues before they occur.

The third technology advancement has been in visualisation. We can now render our geometric designs virtually, in breathtaking fidelity, including previously unfeasible perspectival changes. We can move from a bird's-eye view of the entire building and its surroundings to zoom in on the smallest detail of a room. With the advance of virtual reality, we can now experience digital buildings immersively. We can not only see our designs but also walk through them, experiencing the building long before shovel meets earth. With augmented reality we can merge the digital twin with its corresponding physical building, in order to look at the walls of a building and instantly visualise the infrastructure behind them. We can look at building components such as HVAC and see exactly how they are performing — and where problems may be developing. We can then repair those problems before any failures occur.

REALISATION OF THE DIGITAL TWIN WILL REQUIRE CULTURAL CHANGE

Technology continues to advance, with no signs of slowing. However, cultural change requires that we actively engage, and help people to move from what they have always been comfortable with into this new environment.

Building industry practitioners have traditionally been trained using two-dimensional blueprints and physical models, whilst working in siloed and disciplined environments. Digital twins, however, require that we move to three-dimensional models that are integrated across a range of disciplines. These new technologies are highly disruptive, and as with all major disruptions, people are hesitant to adopt new ways and need to be brought along.

There is also a generational issue at work. Younger generations, so-called digital natives, have never known a world without computers and digital technologies.[30] They adapt quickly to new uses. The older generation are often not as familiar and need more time to adjust. However, they have experience that the younger generations do not possess. The strengths of each generation must be combined effectively.

IMPLEMENTING DIGITAL TWINS IN THE BUILT ENVIRONMENT

We have been developing digital twin-based concepts in other industries over the past decade, but more intensely over the past few years. Digital twins have the advantage that, unlike their physical counterparts, they are not an all-or-nothing proposition. We can choose to collect information only about features that have value, such as the amount of fuel at an airport, the tyre wear of an articulated lorry, or the temperature at a certain point in a power turbine. There is no need to digitally map and monitor the entire asset.

Industries drive digital twin evolution by exploiting specific use cases. We have aeroplane engines that predict future failures. Farmers look at digital twins of their agricultural equipment that know the exact location of the equipment, and can direct units to work together seamlessly. Factory machines schedule their own maintenance, while oil rig manufacturers use digital twins of their platforms to monitor drill bit wear.

The built environment must discover where the information furnished by digital twins can capture value. Relevant use cases can be found throughout the entire lifecycle of design and architecture, construction, and building operation. The challenge is to identify the gaps which technology can fill, and then to iterate and integrate digital twin solutions to produce comprehensive and useful tools. ■

FIGURE 5

Opposite left

The three major advancements that have enabled the digital twin in manufacturing

The two game changers to develop digital twins are: first, data and its availability, and second, computing power.

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INTRODUCTION

The term 'digital twin' has recently entered our vocabulary, bringing with it as many interpretations as instances of its usage. There are two perspectives one can take when considering the digital twin: the first is a critical and dismissive response, the second an enthusiastic embrace of the concepts behind the expression.

Let us consider the first perspective. In July 2018, the phrase digital twin was at the peak of the Gartner Hype Cycle, nestled between 'Deep Neural Nets' and 'Autonomous Mobile Robots'.[31] As of September 2019, 'digital twin' has disappeared completely, replaced by the peak hype of 5G. Digital twins seem to have escaped the 'Trough of Disillusionment', and they have now entered mainstream usage, presumably via the 'Slope of Enlightenment'.[32]

A typical definition of digital twin is as follows: Digital twins are realistic digital representations of physical things. They unlock value by enabling improved insights that support better decisions, leading to better outcomes in the physical world. Connecting digital twins to create a national digital twin (NDT) will unlock extra value.'[33] The critical viewpoint maintains that this type of definition is inaccurate in that there is little, if any, evidence to support the claims of digital twinning delivering extra value or better outcomes. In addition, critics argue that a 'realistic digital representation of physical things' is unachievable, and often ▶

undesirable. These arguments have some merit, but are ultimately too simplistic and overlook the potential of digital twinning.

A digital twin is in part a model of a real system that is coupled with the digital realisation of the abstracted model via data generated by and collected from the real system. A simple linear regression, e.g. of regional power demand on time, may be all that is required to make useful forecasts. Coupling this digital avatar with its socio-physical counterpart yields the digital twin. The result is far from a 'realistic digital representation of physical things'; it is, however, an appropriately abstracted digital representation of an observed complex physical system. Furthermore, it does have the potential to 'support better decisions, leading to better outcomes'.

So what, then, is new? What is different from what engineers, designers, architects, physical scientists, social scientists, and medical scientists have been doing for decades — that is, building abstract descriptive models of systems, making empirical observations of their real-world counterparts, incorporating that data into the models, then using those models to improve systemic performance (or to yield scientific knowledge)?

My personal view on digital twins is inclined to the more positive second perspective. There are two clear differences to what has gone before, and these underpin the novel opportunities presented by digital twins.

The first difference is data and its availability. There is no question that the increasing ability to gather, curate, manipulate, store and retrieve data is transforming all fields of human endeavour, disrupting everything from the political process to commerce to finding one's perfect partner.

Data is the oil fuelling the latest AI revolution — disrupting existing markets while creating new markets in all areas of engineering and related professions. The levels of detailed data available from emerging sensing technologies, from the nanoscale to the global satellite scale, are breath-taking. Data provides the ability to strongly couple a digital avatar to a physical (or socio-technical) system in ways that were unimaginable even a decade previously.

The second difference is computing power, the revolution in software development and the democratisation of high-performance, rapid development computing power.

This is making possible the development of computation-hungry digital avatars, which range from large-scale agent-based simulators of urban landscapes such as transportation networks at the city and regional scales, to complex multi-physics computational fluid dynamics and finite element methods in aeronautics, geotechnics, civil engineering and architecture.
The combination of big data and 'Big Compute' allows us to make sense of digital twinning in a contemporary context, which I believe will 'support better decisions, leading to better outcomes'. The engineering industry must, though, be conscientious In developing data-centric approaches to the full complement of possible applications for digital twins. We must heed our environmental and social responsibilities as stewards of the built environment and of civil infrastructure.

The opportunity to systematically couple data-centric approaches such as digital twins that encompass technical, environmental and social components, their competing criteria, and combined assessments of impact provides one way of answering this challenge. The technical modelling framework supports this endeavour, but working across disciplinary divides is essential. For this, changes in working culture, and not only technical capability, are required. The digital twin concept provides a mechanism via its ability to fuse diverse models and data. We are not there yet, but the direction of travel is promising.

Finally, one can ask what ‘good’ looks like? What do we want to achieve in defining, building, implementing, and using digital twins? What must we include in our thought processes, and what assumptions must we include in our models?

In my view, ‘good’ looks like a strong evidence base of exemplary successes of digital twins that have made the impossible possible, brought efficiency gains to existing practices, transformed inefficient practices, opened up new markets, created multidisciplinary teams working to deliver socio-economic benefit for all. Translating this into measurable KPIs is not a difficult undertaking, but achieving those KPIs is the open challenge to us all. ■

CHAPTER 2

Value of digital twins

Digital twins have the potential to help deliver on many of the grand challenges we face today, including urbanisation, population growth, climate change, escalating infrastructure costs, and sustainable development.

Digital twins hold promise to improve decision making and investment for a broad spectrum of stakeholders, from city-scale transport planners to individual building owners. Potential benefits include everything from better health and wellness in office environments to improved air quality in our dense urban environments. With the digital and social landscapes converging in terms of modelling, sensing and inclusivity, digital twins may be the technology to help deliver on these challenges.

Four emerging themes of digital twins are highlighted in Table 4. Some of the more advanced deployment of digital twins is currently found in the manufacturing sector, with many factories already using twins to simulate production processes. In the automotive industry, the physical system of the cars covers millions of miles, and the digital twin of the car cover billions of miles to robustly enhance their radar and image recognition and vehicle-to-vehicle communication capabilities.[34]

In the aviation industry, engineers are able to pinpoint critical weak spots using digital twins, improving predictions of asset failure.[35] In property, built environment specialists are using sensors and actuators to better understand how people are using the space in which they live and work.[36] This enables proprietors to give occupants more control over their own workspaces and environmental conditions, enhancing tenant satisfaction. The value in linking digital models and simulations with live feedback to provide better design and control is an obvious choice; one that opens up opportunities to deliver improved operations and maintenance, more accurate predictions, more inclusive designs and more sustainable solutions.

While our research highlights issues of detail, of degrees of uncertainty, and of abstraction from the real world, it also highlights the value for our clients across a spectrum of sophistication, setting out a clear framework for stages of improvement and accuracy over time. By applying this evaluatory framework to case studies from five major markets, the research provides exemplars to learn from and to build on.

In the following chapter, we feature a wide range of digital twins varying in scale and levels of complexity, and highlight their benefits, both quantitative and qualitative, across the markets. The benefits include the ability for the digital twin to accurately describe and model our infrastructure in order to efficiently manage and operate it. As this ability develops, the digital twin will attain higher degrees of predictive certainty, leading to more intelligent models which will co-evolve with our infrastructure. We believe that significantly increased automation of our infrastructure is imminent, albeit crucially enmeshed with human co-operation.

Our case studies include, for example, in the Melbourne office, we are collaborating with architects at Hassell to create a digital twin which will support optimal design and usage of office space by leveraging the health and performance data of its occupants. We report a number of projected benefits from the adoption of the digital twin, such as employee turnover, performance productivity and reduction in energy usage. In Amsterdam, we are building a digital twin for the Dutch government's County Hall building in The Hague. The objective of this project is to work with the authorities to determine optimal retrofitting and uplifting methods of the existing structure, in order to achieve an energy-neutral building by 2040. Turning to the water industry, Sydney Water is preparing to invest in a comprehensive digital twin to provide real-time insights into their extensive infrastructure. This digital twin would act as a network of smart meters, and is aimed at saving water, energy and costs.

In the next section, we summarise some key messages from the case studies, thought leadership, and expert opinions gathered together in this report. ■

SUPPLY AND DEMAND	A digital twin can make the entire supply chain transparent by tracking inventory in real-time and then recommending or automating redistribution according to demand. Models of ridesharing networks, for example, can identify demand and redistribute drivers accordingly. In this case it is a twin of an abstract network of drivers, with location data of drivers. Each driver has a digital twin at a lower level of the network, so in fact this can be seen as an instance of subtwins. A simpler example is city parking networks, which can identify underused locations to drive decisions on the reallocation of infrastructure.
OPERATIONAL PERFORMANCE	Numerous examples have shown us how digital twins can continuously monitor operations and identify abnormal behaviour, allowing human operators to react promptly and reduce downtime. They can also apply machine learning for predictive maintenance. For example, we have a sewer system with a prescribed direction of flow. Predictive maintenance can be utilised to identify blockages along the system by applying classification and anomaly detection algorithms. We are able to predict where fatbergs are likely to disrupt the system by using active data such as current rate of flow and historical data of non-biodegradable solid matter present along the system. Other examples include automotive manufacturing plants, power plants, and wind farms.
LIVE DATA MANAGEMENT	Digital twins can help with the management of assets by keeping records of inventory, processes, historical data and additional equipment including manuals and inspection data. This allows owners to identify inefficiencies and ways to address them. For example, we have a physical model of the road network to allow for inspectors to log inspection data to the twin. The data may consist of water leaks, road repairs, underlying utilities and inspection photos. As the twin matures, we are able to optimise the network over time, adapting to various scenarios to facilitate better decision making, both in planning and operation. This information can help to establish annual maintenance and operation budgets and more collaboratively, shared with emergency services in the event of a road closure or diversion. This capability of digital twins holds great promise for facility management and maintenance teams, portfolio and real estate owners, and asset manager.
SIMULATION PURPOSES	Designers and engineers can make use of models, which also fall under the digital twin rubric, for quick, inexpensive prototyping of new ideas, particularly from the standpoint of user experience. These twins can factor in anything from noise to weather, human interactions, lighting, and friction. Digital twins of transport hubs, for example, improve passenger experience by identifying the peak times and better understanding human flow, ultimately resulting in reduced congestion. Simulated systems can include rotors, turbines, engines, trains, aircraft, and autonomous vehicles.

TABLE 4

Above

Four emerging themes
of digital twins

A digital twin can be a powerful tool to support diverse use cases including efficient operations, scenario planning, disruption management, climate, carbon and circular economy outcomes.

ALAN NEWBOLD
Global Digital Aviation Leader
Arup

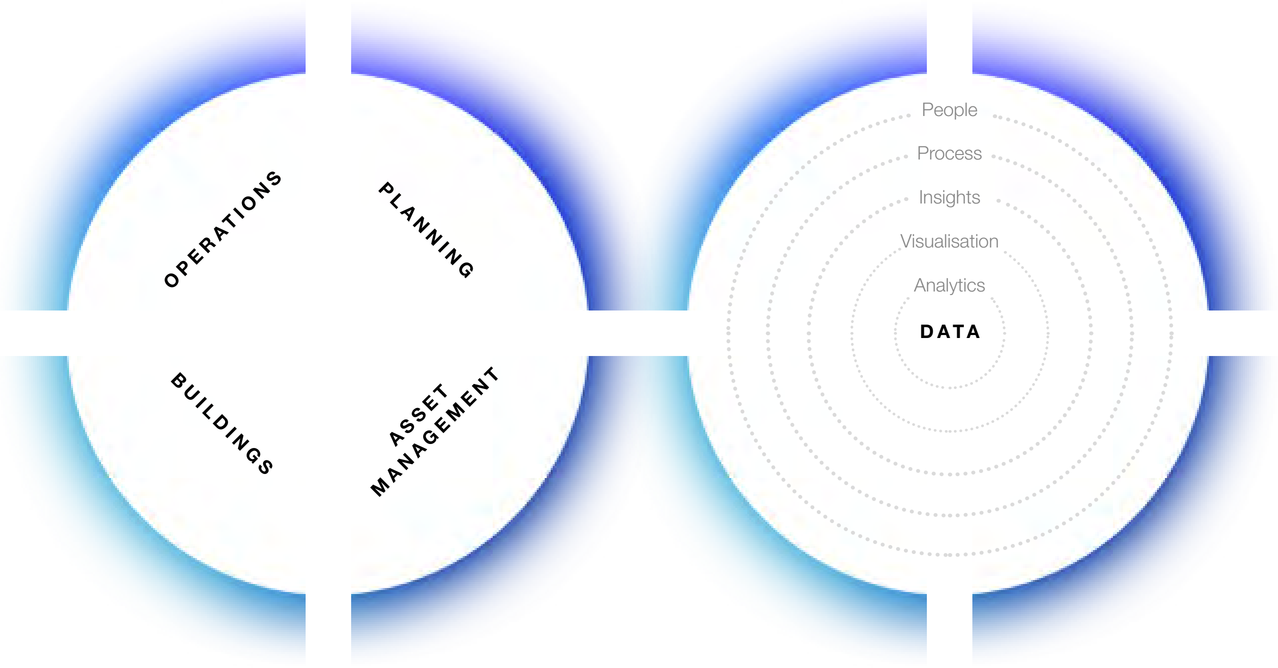
INTRODUCTION

In its simplest form, a digital twin describes a model of an asset that has the engineering detail embedded and coordinated within it that enables engineering and construction firms to perform integrated design and coordination. This is a simple and basic interpretation of a digital twin considering only static data from a single process or area or facility, level 1 if you like.

The outcome achieved here is that the construction director has an excellent digital twin of what has been built and accurately represents what will be handed over to the maintenance team including all maintenance information that could be used to track the assets from a climate, carbon and circular economy basis.

Building on this model, now owned by a maintenance business unit or director, a level 2 digital twin would gather historic usage data and deploy analytics to start to look at scenarios that could deliver improvements to the physical asset or predict things that are going to happen so that these risks and issues can mitigated in advance. This would allow an asset owner to move from a break fix scenario to a predict and prevent model saving maintenance cost and potentially future capital cost through engineering the solutions to actual needs rather than perceived needs or historic engineering standards as well as potentially extending the life of the asset.

A level 3 model could add in real-time data from a currently deployed situation to be able to look at scenario planning in real-time to optimise the use of ▶



the asset making significant maintenance savings and adapting to the actual use of the building. This could all be fed back into the model to simulate any asset replacement or other asset works in the model and choose the optimised solution based upon the customers prioritised requirements.

These three levels would then be the foundation to start to build a more complex and business realistic model by starting to add linked data sets, including weather data to predict how plant may need to perform or occupancy data to look at optimising environmental aspects within the asset.

This scenario only considers the model from a building and maintenance point of view yet there are significant gains to be made in adding in the operational data particularly when considering a retail mall, airport, railway station or hospital.

Moving to a level 4 digital twin you could bring in this operational data (built up in the same way as described previously) to:

- Support decision making and optimisation of the day to day operation
- Make recommendations as to how best to bring a disrupted operation back into normal operation
- Make recommendations as to how and where to improve passenger, customer or staff experience
- Advise on how to increase revenue
- Support decision making and optimisation of the day to day operation

A level 5 digital twin could bring in more data from alternative sources that place this digital twin in its situational context and start to look at this as a system in real-time. This could include people and how they behave, the interaction between surface access and the landside operation in airports or transport data, logistics data and weather data.

Following this you could move a building or operational asset into a set of connected assets and then combine datasets across planning, operations, building and maintenance to deliver a rich virtual representation of the physical environment. This is where a city wide model could really start to offer value to understand the nuanced interactions between parts of a city and be used to offer optimised solutions to the impacts of significant decisions like a new runway at a city airport or a high speed train line and the potential knock on impacts to local transport infrastructure, retail, urban developments and health and wellbeing.

An example of this could be built up in the aviation context thinking about the following flow.

NOW

An airport terminal building that is being constructed using data from the construction model covering all aspects of the static build data; cables, walls, structure, mechanical, electrical etc. The outcome would be a complete set of data on the terminal covering all of the assets that could be handed over and integrated into the asset management system of the airport.

The value of this would be the fact that the asset manager would know exactly what they were getting, how to optimise the maintenance of each asset and details such as the operational lifecycle of the asset to know when it needed replacing. In the near-term it would be expected that operational information will be added into these buildings or asset models so that as the building is operated over time there would then be a data lake of statistics and operating information of the asset based upon what actually happened historically across all assets.

The outcome with this model is that it can inform the planning, design and building of any future airport terminal at the airport as well as provide information to the operating and maintenance team as to how to improve the existing asset. This may also be able to be used to extend the life of the asset and reduce the cost of the maintenance.

NEW

In the near future and with all of this historic data gathered and with the right analytics, predicted models of the building or asset in its operating environment will be available that will enable decisions to be taken to change maintenance regimes to predict and prevent saving significant maintenance costs as well as being able to inform the future planning and designing of the estate on what has actually been used as opposed to designed based upon standards. In addition, scenario modelling can be to demonstrate what would happen in the event of x or y happening and then seeing how quickly you can bring back the asset to a normal state of operation and hence model the disruption caused.

The ability to be able to do this for a building as significant as an airport would enable the airport owner to save money through extending the life of the asset through predict and prevent maintenance, reduce the cost of the maintenance through planned preventative maintenance and hence improving the passenger experience where it is linked to the performance of the asset.

NEXT

Taking this one stage further, this same digital twin could be used in relation to the operation where the asset and maintenance model is combined with the baggage, ground handling and other critical operations to create the airport heartbeat.

Finally, once all of the assets and operations are added to a single model you could integrate this with all 3rd party operations and passengers and their behaviour.

This is the final piece where the digital twin could be a real-time digital representation of the entire Airport and effective run the day to day operation of the Airport potentially resulting in world class passenger experience, optimised non-aeronautical revenues, minimal costs of the operation, very low unplanned disruptions whilst continually improving and learning. This would also give the airport operator a unique ability to scenario plan across the entire operation before implementing and changes and minimise and understand the risks of any investment to ensure a maximum return on that investment.

This vision will become a reality over the next five or more years as airport operators start to see the benefits of their current proof of concepts in this space and become more connected data driven organisations across their planning, building, operations and maintenance structures. ■

FIGURE 6
Opposite left
Most digital twins currently are addressing a single isolated use case in one of these four quadrants

FIGURE 7
Opposite right
An overview of a single model using asset and operational data

There are many IoT devices being developed and rushed to market, yet they are not being designed, from the onset, with security in mind.

CHRIS LYTH
Global Head of Cyber Security
Arup

INTRODUCTION

What does cybersecurity mean for digital twins? Cyber security is always a challenge in a fast evolving digital landscape. The convergence between the physical and the digital worlds means that cyber security will need to underpin the digital elements of the built environment. Cyber security is a fundamental component of delivering business resilience. In an increasingly connected world more and more devices of all sorts are being connected to the internet, thus leaving a huge potential attack surface. There are a huge number of IoT devices being developed and everyone's rushing to bring these things to market, and they're not designed, from the outset, with security in mind. This is an issue for us in the security team and we're going to need to develop the right frameworks to enable IoT devices to be used securely.

At Arup, there can be a perception that the security team will turn away requests as they may be seen as security threats, but we want to be in a position to enable innovation and collaboration and facilitate people to do what they want, albeit in a secure way. I think there is definitely a place for digital twins, but businesses will have to balance risk versus reward. As with all of these things, we are living in and moving towards an increasingly collaborative and open environment. We need to think and build in from the ground up how we plan to share, collaborate and work with digital twins securely - be it in an open, closed, shared or federated way. Core security principles need to be carefully considered and a proper security architecture put in place to develop safe and secure digital twins.

When we are designing digital twins, we must consider the CIA triad — confidentiality, integrity and availability.[37] Confidentiality of data must be viewed from the perspectives of data sensitivity and intellectual property. As you start to build up these models, and you have more and more data in there, and they become more federated, then there's a huge amount of intellectual capital that effectively sits in those models. We will have to think about how we protect our commercially sensitive stuff, because that's essentially our business. ▶

We also need to ask ourselves what would happen if the data were to get into the wrong hands (e.g. models of critical national infrastructure (CNI))? For example, terrorist groups or nation states; these days, we are increasingly seeing nation states using cyber weapons to attack each other. If digital twins become linked to control systems in the physical world you may end up with potential compromise of physical control systems — e.g. manufacturing, building management systems, CNI control systems, etc. With digital twins, confidentiality of data is going to be important. It's not just having the right data in there to make decisions with, it's also protecting that data from unauthorised access.

When we think of open, shared and federated models, we need to consider who is that open to and shared with, how far does that go? For publicly available data, effectively, in these digital twins, there are limits to what you're actually going to be modelling, because you don't want data to get into the wrong hands. There is a lot of sensitive data out there which we will want to protect.

Considering integrity of information, we need to make sure the data in the digital twin is correct. If we plan on operating higher level digital twins this will be critical since real-time decisions in the physical world will be made based on the data within the digital twin. For a level 1 digital twin, this is less critical. Increasingly the integrity of data will come under attack. Malicious actors will inject false data into data sets and systems and real-world decisions may become compromised.

There was the widely known Stuxnet case in which a cyberweapon was created to cause substantial damage to Iran's nuclear enrichment facility.[38] Stuxnet was a piece of code which intercepted data from the centrifuge sensors and reported back to the control system that everything was operating as normal. In reality, the code was speeding up and slowing down the centrifuges beyond their tolerance levels until they broke. The integrity of the data in the system was compromised. This attack set the Iranian nuclear programme back by two to three years. With many of these types of cases, the facilities or assets are controlled remotely. The sensors and actuators are there to partially or fully replace human inspection. Depending on the level of interaction with the digital twin, we need to work out how much decision making will be granted to it.

Imagine another scenario where we have sensors deployed in a bridge to predict maintenance requirements. Say that you wanted to intercept and falsify the sensor data for malicious purposes: intending to cause a failure in the bridge.

We would set all that sensor data, passing it on as if everything were fine, while in reality the bridge may be experiencing some kind of engineering failure. The integrity of data and knowing that you've got the right data — this is critical.

For availability, if you're using digital twins to make decisions in the real world in real-time, and you're using that data to control things, then imagine the scenario in which your internet goes down, or your model goes down — what happens then? Look at the WannaCry cyber-attack, which cost the NHS £92m — £73m of which was spent on IT costs to rectify the problem.[39] Over 19,000 appointments were cancelled. When we refer to availability, we need to consider disaster recovery as a key component within the move to digital twins. We need redundancy built in. These days we tend to distribute our infrastructure to many different cloud platforms, and building in a distributed architecture is key. We cannot rely on a single model in a single place. When we distribute over a different number of environments or cloud providers globally, then if one or two go down, we are still operating.

The level of engagement in each of these areas comes down to the sensitivity of the data and system involved. If you're developing a digital twin, ask yourself the question: what is the impact if it gets into the wrong hands or things go wrong from a confidentiality, integrity or availability perspective? If we are operating in environments of higher sensitivity or greater risk then the conversation about security investment in these areas is one to have. The key things that need to be in place can be found in Table 5. ■

SECURITY
Right from the start when we are thinking about digital twins, the models and the architecture, we need to treat the security aspects as fundamental.

DATA ENCRYPTION
Data will need to be encrypted in the model, both at rest and in transit. ‘At rest’ means that data is not only encrypted as it travels from devices to the digital twin, but also within the digital twin itself, under all circumstances.

IDENTITY AND AUTHENTICATION
Identity is going to be at the heart of security for digital twins. We need to understand who is trying to access what, not just from the user perspective, but also in terms of who is sending us data. Authentication is a core part of identity: how do I know that the right device is sending the right data to inform the digital twin, or vice versa? Devices and users will need to authenticate in a secure way, and the whole concept of identity will therefore be central to digital twins.

PRINCIPLE OF LEAST PRIVILEGE
This refers to applying the correct access rights: allowing users to access what they need in order to perform their role (internally and externally), and no more. Sharing the entirety of the model needs to be carefully considered as there may be highly sensitive data to protect. Aggregation of data may also increase its sensitivity.

SECURITY AUDIT
We need visibility of all transactions, to be sure that the right devices and users have the right level of access and what activities they have performed, etc.

MONITORING LIVE EVENTS AND RESPONDING TO INCIDENTS
We want to be in a position where we have visibility and monitoring in our live environment. We want to be able to detect anomalies in real-time, and to provide effective incident response. The live monitoring of environments is going to be increasingly AI-driven, using behavioural analytics and anomaly detection.

MANAGEMENT OF DEVICES
When do my devices need to be updated and patched and how do I perform this? The secure management of networks of millions of devices will need to be considered carefully.

TABLE 5

Above

Seven pillars of cyber security to consider for digital twins

The increasing amount of data that buildings and infrastructure will generate in the future poses a new challenge to the built environment sector. Despite many years of experience in the security and longevity of physical assets this industry never really had to deal with the same aspects for the virtual counterparts.

MATTHIAS GEIPEL
Senior Consultant
Arup

We are increasingly making demands that we have previously only made on the apps on our smartphones allowing for connectivity, adaptability and long-term support through function extensions and security updates. This attitude extends inexorably to other areas of our lives. From the vehicles we use to the buildings we stay in.

But even without this recent demand of its users, the high availability of sensors and information processing technology is one of the main reasons for an increasingly networked built environment. A variety of interests and incentives play a role in this, deciding who wants to install and use which data sources. The interests differ widely. From the user who would like to have a better overview of his energy consumption or air quality, to planning offices who would like to better understand the effects of their planning on the operation, to the facade manufacturer for whom data on the performance of his installed facade solution can be valuable and last but not least, of course, the building operator himself. The vested interests, combined with the increasing availability and decreasing acquisition costs of suitable hardware and the associated platforms, will ensure that our buildings, in addition to the typical technical building equipment, will be more and more strongly permeated with the technology resembling the human nervous system. If you add up the existing and the real-time data, they become a digital image, the twin of the physical asset. ▶

This development raises two important questions:

1. **HOW CAN WE ENSURE THAT THIS INFORMATION REMAINS USABLE FOR DECADES?**

2. **AS WELL AS THE INCREASINGLY IMPORTANT QUESTION OF DATA SECURITY?**

For example, let's assume an office building built in 2020 with an expected end-of-life in 30 years. Looking back, this corresponds to the challenge to store data in 1990 in a complete, secure and legible form to this day. How much of the digital information from 1990 is still available today? As a reminder, in 1990 there were no cloud service providers in the current sense, the CD-ROM just started its victorious career (is anyone still using optical storage media today?) and smartphones and social networks simply did not exist. This example shows what a challenge we face in view of the flood of data from digital building twins. The tools and platforms we use today may not be the ones we will use in 30 years' time.

But let me address the second, equally relevant challenge. It involves the security of the data that is generated. Security against theft as well as security against manipulation. The past has shown one thing, namely that data, whoever it is entrusted to, is not actually safe from any of these dangers. If the size and therefore often the reputation of a data processing company increases, hackers' interest in this "honey pot" also increases. In the recent past, for example, neither state owned personnel service providers nor Internet marketplaces nor global consulting agencies were safe from being attacked. The motivation for such intrusions is multi-layered and ranges from political-strategic reasons and economic incentives to pure vandalism.

What we are currently ignoring in this observation is the fact that information from a digital twin will in future be attributed value to by its very existence. Performance-related information of an office building is directly valuable for the building operator and indirectly valuable for the operators of other buildings. Planning and operations information of economically, infrastructurally or military highly sensitive facilities is valuable for other reasons.

Systems that handle this data do not only move pure data records but handle assets. The storage and transfer of such data therefore places more demands on a bank-like infrastructure than on any data room. This approach makes it clear why a focus should be placed on data security. For BIM data, the British Standards Institution has already published PAS 1192-5, a standard that addresses this exact concern.[40] More precisely, in the context of digital planning, building and operation, it is a matter of securing the following properties of each piece of information: safety, authenticity, availability, confidentiality, integrity, possession, resilience and utility.

Until 2008, there were no major leaps in the area of information security. Rather, we are still widely using cryptographic methods from the 1970s.[41] Not without good reason, because these concepts have proven themselves over many years and have been tested and improved many times. The author of the bitcoin whitepaper published in 2008 also made use of various existing ideas, but was able to answer a fundamental question in information technology: "How do I create something digital that can't be copied?"[42] A new milestone in data processing has been set with the concept that today is largely referred to as Blockchain Technology.[43,44]

For the first time it is possible to carry out a digital, global and instantaneous value transfer without the need for a central instance.

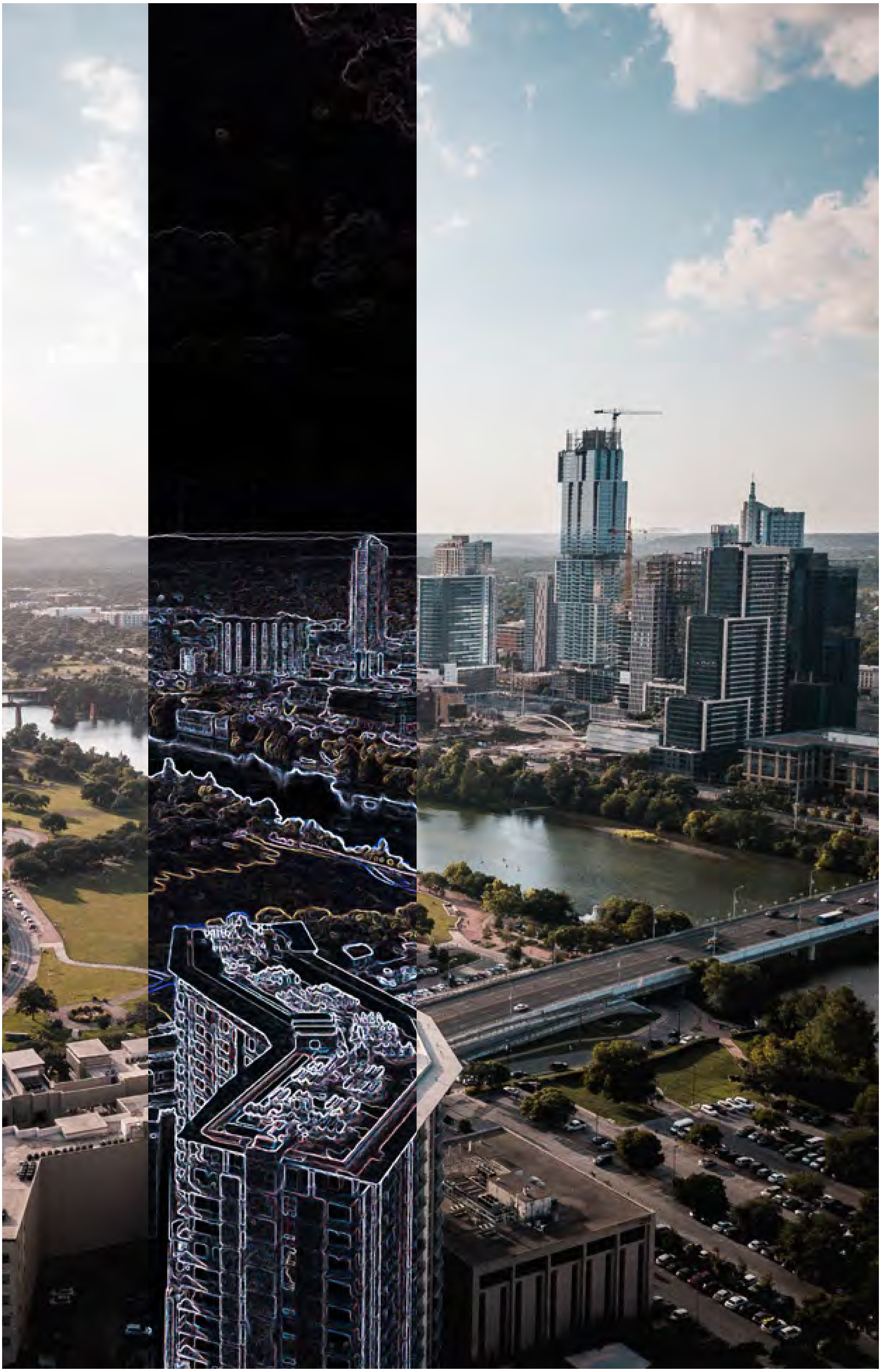
The processing is carried out by a physically and organisationally decentralised network. A censoring or manipulation of such a transaction is virtually impossible. A fascinating possibility with regard to the aforementioned exchange of data between a building and its digital twin and vice versa. If one considers how global the real estate market will be in the future and how many cultural and political interests will play a role in a single property, it is good to know that one is not dependent on individual actors when it comes to the transaction of valuable building data. Private providers offering value exchange services are not uncommonly forced to discontinue their services for certain applications or in certain jurisdictions. A dependency one would like to do without in critical infrastructure and building operations.

The data security of digital twins can furthermore be increased with the help of blockchains, in which the networks are used to document unalterable and audit-proof snapshots of consumption or sensor data. Due to their decentralised nature, the data here is safer from manipulation than it could ever be in a centralised platform.

But also the storage of the actual, complete data model can now be left to decentralised networks. Analogous to the value transfer just described, a network of economically incentivised participants distributed across the globe is used here to offer high availability and data security online storage.

The cases of data misuse and data loss from the past are reason enough for us to think about the collection, processing and storage of building data, especially considering the value the data around a digital twin will gain in the future. With blockchain technology, we now have a tool at our fingertips that allows us to follow a new path. A path that will exclude some intermediaries but at the same time enable new business models.

We only have to evade the assumption that every blockchain, no matter what form it takes, leads to this goal. I therefore recommend taking a look at the already existing, open, well-tested blockchains first. Just like in cryptography where we still use the well tested, open standards to secure our communication. ■



Cities

Cities have been described as humanity's greatest achievement. Their growth is certainly accelerating: more of us live in cities than at any other time in our history.

LÉAN DOODY
Smart Cities Leader
Digital

Rapid urbanisation offers opportunities for sustainable development, as services such as healthcare, housing, infrastructure, transport, energy can be more efficiently delivered in a more densely populated environment. However, delivering these services to a rapidly growing population will be challenging. John Wilmoth, Director of UN DESA's Population Division, says "Managing urban areas has become one of the most important development challenges of the twenty-first century. Our success or failure in building sustainable cities will be a major factor in the success of the post-2015 UN development agenda."[45]

Recent research by C40 shows that urban policy decisions made before 2020 could determine up to a third of the remaining global carbon budget that is not already locked in by past decisions.[46] So, the decisions made by city leaders will determine whether or not the world is set on a high or low carbon pathway. Mayors and city leaders are therefore key actors in delivering a just transition to a low-carbon economy.[47] We need to make sure they are equipped with the data and tools they need to make effective decisions. Smart cities and digital twins offer some possibilities.

The concept of the smart city has existed since 2000.[48] The basic idea of the smart city is one in which digital technology and data are used effectively to address urban challenges. This is no longer such a radical idea as in 2000, when digital technology was still very much the purview of the office, the iPhone had only just launched and digital platforms like Uber and Airbnb were still seen as the wave of the future. Since then, we have seen the digitisation of city infrastructures providing real-time transport data, energy data from smart grids and smart metering, mobile phone data tracking the movements of whole city populations. ►

This proliferation of data creates the possibility of using it to address our city challenges through better-informed decision making, improved performance and optimised resources. But city challenges are multi-headed — transport congestion is linked to access to housing, air quality, and employment.[49]

The promise of the city digital twin is to help provide a simulation environment, to test policy options, bring out dependencies and allow for collaboration across policy areas, whilst improving engagement with citizens and communities. This could be transformative.

This all depends on having the right processes and governance around the digital twin. For example, a digital twin could be used to help citizens understand and propose development options and trade-offs, and therefore build political and community support for beneficial infrastructure investment. Successful outcomes will not only require the digital twin to be designed for the purpose of engagement, perhaps incorporating user-facing visualisations and tools, but will also need participatory processes such as events and meetings.

However, the experience of smart cities has shown that city governments have struggled to incorporate technology and data strategically. This has included issues relating to leadership (including knowledge and capacity), political boundaries, collaboration with multiple stakeholders (public and private), enabling R&D and urban innovation. The same issues will apply to the adoption of city digital twins.

This is an area ripe for research. The Cambridge Centre for Smart Infrastructure and Construction, supported by The Ove Arup Foundation, has established a project entitled 'Digital Cities for Change', with additional funding from the Centre for Digital Built Britain.[50] The research team is currently developing a digital twin pilot for the Cambridge sub-region in collaboration with local authorities. The Cambridge Digital Twin pilot project will test how isolated policies from transport, housing, environment and energy can be bridged using the digital twin, and quantify some of the interdependencies among transport, air quality housing and energy infrastructure in relation to changes and uncertainties.[51] Importantly, the work will test how the Cambridge Digital Twin can be combined into the workflows of the local authorities and used with other models, or whether it should remain a standalone tool. This will help us to understand how best to design digital twins and their associated governance and processes, so that they can be used on an ongoing basis by city governments.

Data ethics is another area which needs further discussion. The ethical implications of widespread use of new technologies are not clear, although for example, although there is increasing disquiet about privacy and use of personal data to target people for political ends. Privacy, trust and surveillance are key issues, particularly with more widespread deployment of IoT technologies — one question is how to get people's consent and build trust. The Centre for Digital Built Britain has published The Gemini Principles, which provide high-level guidance for the development of digital twins and are a useful step in this direction.[33] There will need to be further debate and discussion at at the societal and political levels about the benefits and tradeoffs of data ownership and privacy before we see a consensus in this area.

The city digital twin holds great promise to help city governments make more informed decisions with citizens, identify systemic risks and enable city infrastructures such as transport, energy, housing to work in concert more effectively. In our enthusiasm for the technology, we must not forget that it is always human beings who use it. We must design human-centred digital twins that can fit with our existing organisations, even as they help to change them. ■

QUESTION AND ANSWER

The internet is becoming the Internet of Things; a fusion of bits and atoms. As a result, every atom has a digital counterpart — or a digital twin.

PROFESSOR CARLO RATTI
Director
MIT Senseable City Labs

TELL ME A BIT ABOUT YOURSELF, AND WHAT YOUR LEVEL OF ENGAGEMENT WITH DIGITAL TWINS HAS BEEN?

CR I am an architect and engineer, and I wear several hats, as the English would say. Firstly, I lead the design and innovation firm CRA [Carlo Ratti Associati], based in New York, Turin and London.[52] Secondly, I direct the Senseable City Lab at the Massachusetts Institute of Technology, in Boston. Finally, I am engaged with a few start-ups. Although each activity focuses on a different area — research, projects, or products respectively — the vision is always the same, and it deals with the impact of digital technology on the way we experience the built environment. In this sense, even if I havenot much used the digital twin label itself, it is central to what we do.

WHAT IS YOUR DEFINITION AND VIEW OF A DIGITAL TWIN?

CR I see digital twins as reflecting current broad technological trends: the spaces around us are becoming permeated with digital technologies and data. The internet is becoming the Internet of Things, a fusion of bits and atoms. As a result, every atom has a digital counterpart — or a digital twin.

HOW DOES THE HUMAN FIT INTO THE DIGITAL TWIN?

The human must always be at the centre. As advances in digitalisation are probably inevitable, we should not forget that it will be humans who determine how they will affect us. I'm reminded of a very interesting piece that former Secretary of State Henry Kissinger wrote in The Atlantic some months ago. Starting from a compelling historical comparison with the spirit of the Enlightenment, he warns about the danger of mistaking machines' capability for "unprecedented memorisation and computation" with actual human intelligence, which is based on thinking.[53] "AI is likely to win any game assigned to it. But for our purposes as humans, games are not only about winning; they are about thinking. By treating a mathematical process as if it were a thought process, we are in danger of losing the capacity that has been the essence of human cognition."

HOW WILL DIGITAL TWINS TRANSFORM THE INDUSTRY?

CR I think that the consequences will be profound. For instance, I believe that the traditional jobs of structural and M&E engineers will disappear — AI can do them very easily on a digital twin model, at a fraction of today's time and cost. I believe that the only engineering that will survive in the medium term will be the one with a creative angle — à la Ove Arup…

Construction itself will also change radically, with digital twins allowing components to converge on a site just-in-time, before being assembled in a similar way to how we assemble cars or airplanes today. And the monitoring of a building will continue within the same digital twin framework. Basically, we will see changes across the whole chain.

WHAT ARE DIGITAL TWINS ABLE TO SOLVE, MEASURE, OR DO BETTER?

CR Beyond what we were just saying about the construction industry, digital twins will have a broader impact on our cities. Linking the physical and the digital would allow us to better measure our built environment, and with the additional layer of information we would gain, we could respond to it in more tailored and efficient ways. This could take the form of digital sensors dispersed throughout the physical world, capable of supplying the necessary information to update the digital counterpart on a variety of elements. A digital twin would then be in a position to make calculations and combinations based on the data obtained from these measurements, providing information on how to transform the physical infrastructure.

We have been interested in how real-time (live) data can change urban dynamics ever since the beginning of our work at the Senseable City Lab at MIT.[54] This was, for instance, the focus of our Real Time Rome project at the Venice Biennale 2006, a world premiere in the use of live cellphone data in a large city.[55] In it, we aggregated data from cellphones (obtained using Telecom Italia's innovative Lochness platform), buses and taxis in Rome to better understand urban dynamics in real-time.

This project shows how one of the most important technologies for the future of our cities may be our cellphones, which already have very evolved sensors — so evolved, in fact, that in a project at the SCL, we used them to measure the vibrations coming from Harvard Bridge. We placed smartphones on two cars crossing the bridge and used the data they collected to measure the bridge's structural health. Smartphones, in fact, are equipped with three accelerometers that are able to measure the movement of the phone on three axes: height, length and depth, and to register a series of data of varying importance. This is an example of the way a mobile network could be a cheap way to supplement and improve a network of fixed sensors. Digital twins would need to leverage similarly dynamic sensors.

Such measurements could give us an idea not only of the structural health of infrastructure, but of the needs and desires of users. This is what we tried to do with our renovation (as design and innovation practice Carlo Ratti Associati) of the Agnelli Foundation HQ in the heart of Torino.[56] In collaboration with tech company Siemens, we equipped the building with hundreds of ▶

I believe that the only engineering that will survive in the medium term will be the one with a creative angle.

▲

FIGURE 8

Above

Carlo Ratti Associati equipped the Agnelli Foundation HQ in Torino, Italy, with hundreds of digital sensors that allow occupants to choose their preferred environmental settings, creating responsive micro-climates

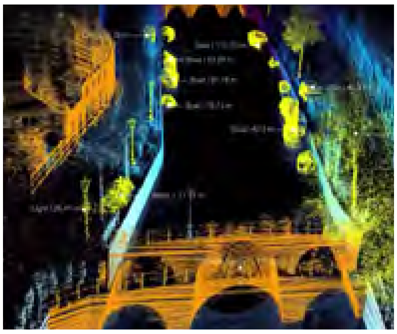


FIGURE 9

Above

MIT Senseable City Lab's fleet of Roboat units, which were first tested in Amsterdam's canals, could be used as agile sensors to gather data on the city's infrastructure, as well as air and water quality insights

digital sensors that monitor different sets of data, including occupancy, temperature, carbon dioxide level and the status of meeting rooms. Users can access this monitoring platform through a mobile app that enables them to interact with each other, check in, book meeting rooms and regulate environmental settings, all with an unprecedented degree of personalisation.

For instance, once a building occupant sets her preferred temperature and illumination settings, the building management system responds accordingly, adjusting the levels of lighting, heating and cooling. As the fan coil units situated in the false ceilings are activated by human presence, the system can potentially follow occupants as they move around the building, just like an environmental bubble. When an occupant leaves, the room returns to standby mode and conserves energy, just as a computer would do with a screensaver.

WHAT ARE THE TECHNICAL CHALLENGES OF DELIVERING DIGITAL TWINS?

CR I think that things are coming together. However, I am concerned about the data ownership issue. Today there is a risk of data asymmetry, with just a few companies and public institutions knowing a lot about us, while we know so little about them. There is a real danger of data monopolies and data misuse by both large corporations and governments. At our MIT lab, we instead seek to investigate how big data can be used to improve life in cities for inhabitants. We publish all the research and data we collect from our projects online, creating platforms that can be expanded with user-generated content so as to inform policy-makers, companies and citizens alike. We have also been working extensively on the ethical and moral issues connected to big data. In 2013, we launched an initiative called 'Engaging Data', involving leading figures from government, privacy rights groups, academia and business.[57]

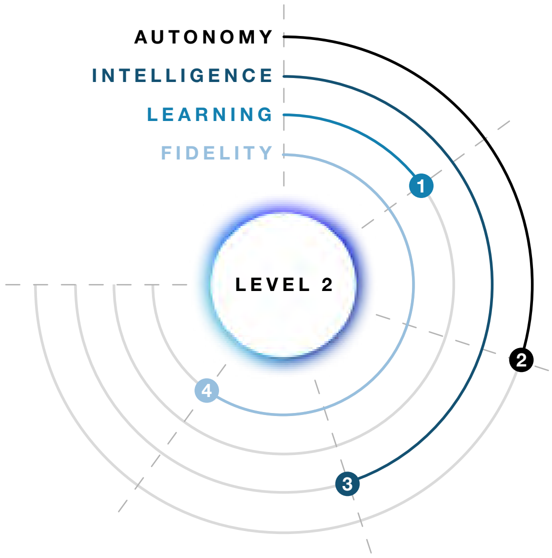
WHERE ARE THE OPPORTUNITIES FOR DIGITAL TWINS IN THE ARCHITECTURE, ENGINEERING AND CONSTRUCTION INDUSTRY?

CR Apart from some of the streamlining issues we have discussed before, I think that digital twins have the potential to redefine the very meaning of a building. Architecture has been called a third skin that envelops us atop our biological skin and our textile skin — clothing. It has often been the most uncompromising of the three, rigid and unable to adapt to the changing needs of different occupants. Yet, as the IoT revolution unfolds, with a widespread fusion between the physical and the digital, architects are beginning to imagine how this third skin can develop responsiveness, learning from people's needs. ■


AON
ONE WILSHIRE
CITY NATIONAL BANK
WESTERN

CASE STUDY: ARUP CHINA / HONG KONG

Digital twins for Neuron City



BACKGROUND AND MOTIVATION

China is one of the world's leading testing grounds for smart cities. Arup Hong Kong is building a city scale digital twin platform to map space, people, and activities in the physical city to a virtual city. The digital twin incorporates GIS, BIM, IoT, cloud computing and AI. Although many pilot projects exist on the market, they tend to follow a similar profile: they are often targeted at testing or showcasing computational capabilities, rather than at solving real-world problems. They are often too fragmented, isolated systems such as transportation or security and in general, with a low degree of artificial intelligence. Therefore, we built a platform that is able to overcome these challenges. With the help of our city planners and design team, we are able to bring this to life.

We built a digital twin of Hong Kong city called Neuron City. The platform maps the physical spaces and people to a virtual city (i.e. the digital twin). We are able to monitor, predict and control aspects of the physical city by incorporating a closed-loop data stream. This has lead us to solve rather complex problems in the urban lifecycle.

PROTOTYPE

The Neuron City prototype is shown in Figure 10. Our first-stage work was completed in 2018/19 where we built a city scale information model (CIM) platform operating system. The prototype included the following functionalities:

- 3D modelling and spatial analysis
- Visualisation of simulation data and statistics
- Building data dashboard
- Parametric design module
- Real-time data visualisation and analysis.

PROJECT APPLICATIONS

The project integrated an IoT data management platform. We produced a demo of the complete design scenario and implemented a machine learning algorithm to provide predictions using city-scale data. ▶

Digital twins of cities map space, people, and activities in the physical city to a virtual city. By building closed-loop city-level data into the virtual city, monitoring, prediction and control of the physical city can be achieved, in order to solve complex problems of the urban lifecycle.

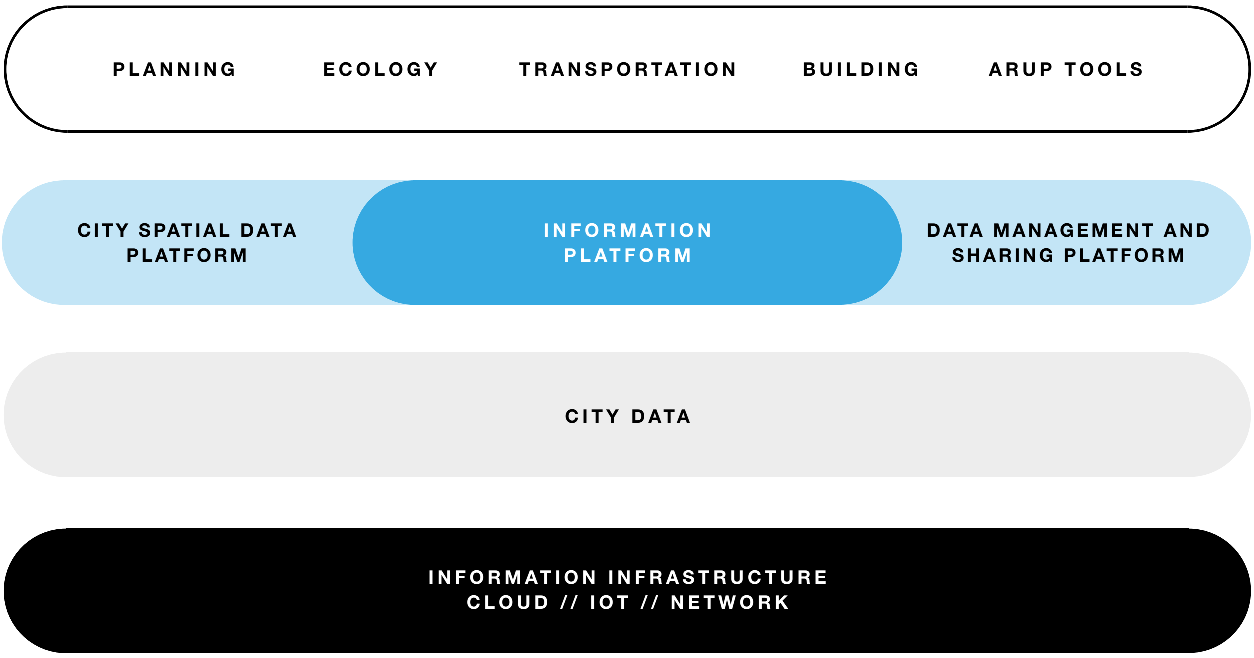


FIGURE 10
Above
A holistic view of the Neuron City framework

FIGURE 11

Opposite top

By building closed-loop data into the virtual city, monitoring, prediction and control of the physical city can be achieved, to solve the complex problems of the urban lifecycle

FIGURE 12

Opposite bottom

Distribution of air pollution, as simulated by the digital twin

VALUE

The value of the first-stage work consisted of building the CIM platform which was used in several projects to demonstrate the added value to our design. The platform adds value by integrating data for collaboration and decision making, and by developing innovative city prediction and control applications. The value generated can be captured in the two examples listed below:

Distribution of house prices
Online house price data was collected and visualised by location as part of Neuron City. This provides a quantitative basis for decision making and greater insight into the housing market.

Multi-source spatial analysis
We used the 'landsat' multispectral remote sensing image to achieve a specific land type distribution by generating a Normalised Difference Moisture Index raster image.[58] This has allowed us to achieve remote sensing to higher degrees of accuracy and precision.

FUTURE WORK

Future plans for this platform includes establishing a data pipeline, collaborating across the wider ecosystem and developing partnerships with integrators and suppliers to continue to solve complex problems in the urban lifecycle. In the next two years, we plan on launching a market-ready commercial product with the aim of incorporating more intelligence and learning into our platforms. ■

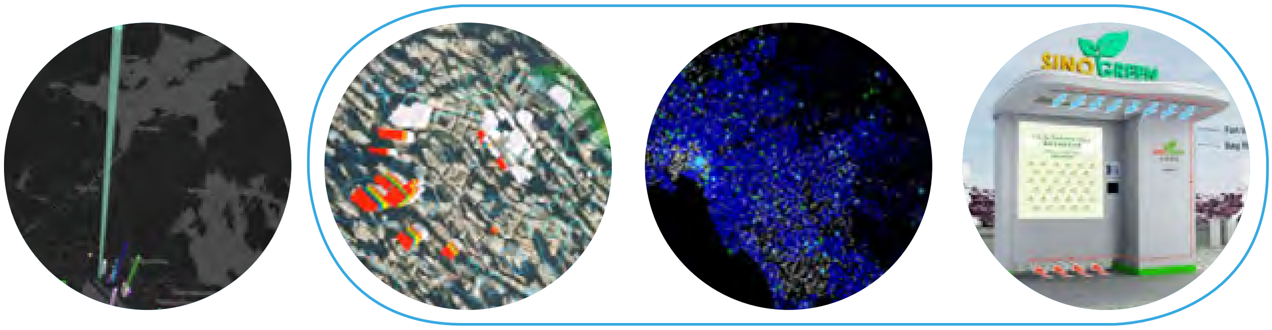
MEET THE TEAM

ALLISON AN
Analyst

BRUCE CHONG
Associate Director

QIAN CAO
Senior Engineer

Y WANG
Associate Director



SENSING

IoT data

ANALYSING AND FORECASTING

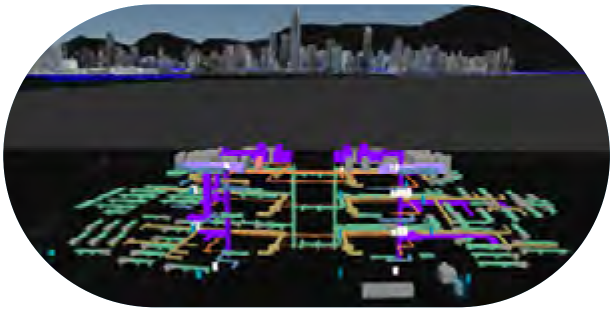
City modelling
and simulation

Big data forecast

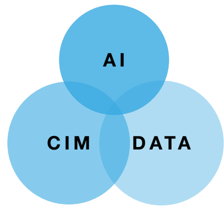
RESPONSE

Intelligent response

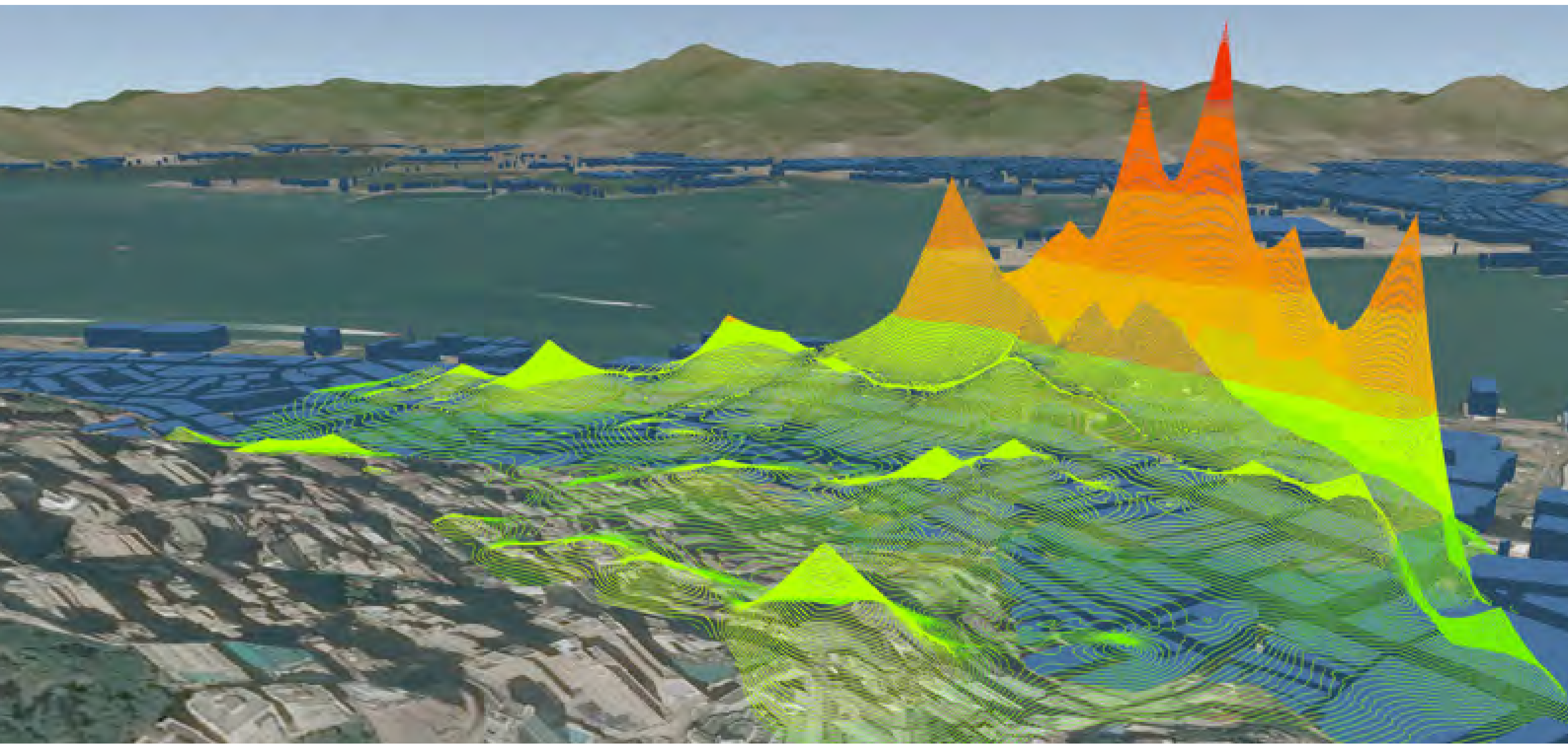
CITY INFORMATION MODEL
= GIS + BIM + IOT



ANALYSIS AND FORECASTING



DIGITAL TWIN



QUESTION AND ANSWER

A smart city digital twin is an IoT-enabled virtual platform that has some kind of data richness, real-time information, and where we can see what is happening in the city.

PROFESSOR JOHN E TAYLOR
Associate Chair for Graduate Programs and Research Innovation & Frederick Law Olmsted Professor
Georgia Institute of Technology

TELL US A LITTLE BIT ABOUT YOURSELF AND WHY YOU ARE INTERESTED IN DIGITAL TWINS.

JT I'm a civil engineer who does a lot of computational work. As I look at what is happening across universities, I see that a lot of the discussion seems to centre around the computational and technological issues related to smart cities, but I don't see as many civil engineers or infrastructure experts at the table. Ultimately, IoT sensors are going to be placed on infrastructure, so I think architects, civil engineers and urban planners need to be a part of this — right in the centre of the conversation.

WHAT IS THE DIFFERENCE BETWEEN A DIGITAL TWIN AND A SIMULATION?

JT For me, digital twins are about machines. You create a virtual representation of the physical world by pumping in real-time data about some system and monitoring it, so that you can anticipate a problem before it occurs. You can also use simulation to predict — given its current state — when a machine may need maintenance, or when it may wear out on the assembly line. I think what differentiates this from simulation is that the answer it gives you today will likely be very different to the answer it gives you a week from now. This is because it is based on the flow of real-time data. It is a continuously updating simulation that allows you to predict future states.

HOW DOES A MACHINE DIGITAL TWIN DIFFER FROM A SMART CITY DIGITAL TWIN?

JT When we define the smart city digital twin, we are talking about an IoT-enabled virtual platform of a city that has the kind of data richness and real-time information which allows us to see what is happening in the city. We can start to analyse it to understand why things are happening the way they are happening, and then we can simulate what-if scenarios. One difference is what is being measured. When you move to the city scale, you have to include humans in the loop. What I've learned from the manufacturing assembly line is that humans certainly play a role in the degree to which machines wear out. In a city, if you're going to study energy use, humans are the ones who are making decisions about that energy use. If you're going to study transportation, humans are the ones driving the cars. Human-infrastructure interfaces become an important part of the definition of smart city digital twins.

HOW WILL HUMANS INTERACT WITH DIGITAL TWINS?

JT We can boil it down to two broad classes of interaction. On the one hand we have what we call in the built environment the facility manager, who interfaces with a building energy management system in a very different way than does the occupant of the building. At the city level, we also have maintenance and operations for services in the city; there would be an interface for those users to see what's happening across all system in the city.

The way we are developing this type of interface is through augmented and virtual reality tools that put people in front of the data. We can put data in front of users in contextually realistic ways. We can put city managers at the actual intersection, where they can then analyse the data. They can look at different aspects that are occurring around that intersection while they pull out different bits of data and do visual comparisons and correlations.

The way we interface with citizens is a bit different. Just as we build feedback systems for buildings, we must engage occupants in the process too. We have been gathering information about what's happening in the city and allowing occupants to input their needs and preferences though smartphone applications: this combines basic app development with augmented reality. They don't need full immersion in virtual reality; they just want to contribute what they have to say about this building here or that bike path there. ■

A digital twin is a continuously updating simulation that allows you to predict future states.

CENTRE FOR DIGITAL BUILT BRITAIN

National Digital Twin Standards — Gemini Principles

The Gemini Principles report was published by the Centre for Digital Built Britain in December 2018.[33] It aims to align approaches to information management across the built environment, since 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 for the Built Environment 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.

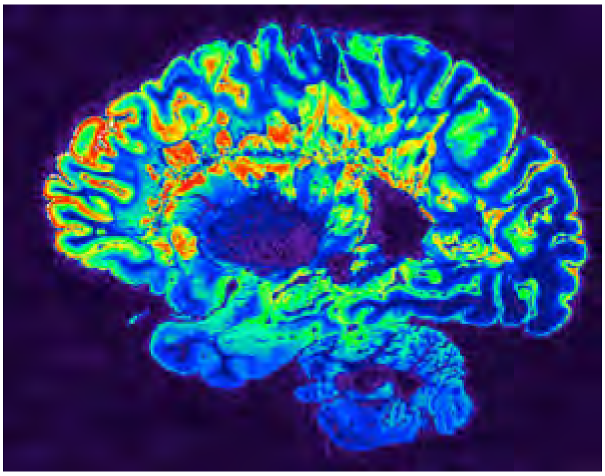
Enshrined in these values is the notion that all digital twins must have clear purpose, must be trustworthy and must function effectively. All the Gemini Principles flow from this. They are intentionally simple, but their implications are far-reaching and challenging. They are descriptive of intent,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

PHILIPS HEALTHCARE

The digital patient in healthcare

Philips Research asks: if a digital twin of an MRI scanner can help predict which part will need replacing, could the same concept be applied to discover and treat ailments in the human body before they become apparent?[59] By integrating different measurements of a person, a digital model of a body part, such as their heart, could be built. Eventually, an integrated model of their anatomy and physiology could be constructed.

The vision is to have a personalised, lifelong patient model that can be updated with each measurement, scan or examination, and that includes behavioural and genetic data as well. The digital patient could bring together all a patient's information to support diagnosis and treatment.[60] In future, it might be possible to predict diseases and provide treatment and prevention plans unique to the characteristics of an individual patient. Digital twins for the whole human body could usher in an era of personalised medicine.



VIRTUAL SINGAPORE

World's first city-scale digital twin

From bus stops to buildings, Virtual Singapore is a data-rich, live digital twin developed to produce a central platform for the modelling done by different government agencies.

The digital twin draws on IoT sensors, big data and cloud computing, combined with 3D models, geospatial datasets and BIM. Virtual Singapore was co-developed with the French firm Dassault Systèmes, by leveraging its existing software platform.[61]

The interplay of map and terrain data, real-time traffic, and demographic and climate information show how a single change could affect the lives of millions of people, and the systems they depend upon. Virtual Singapore offers a platform that can be used by urban planners to simulate the testing of solutions in a virtual environment.

NEW SOUTH WALES (NSW) GOVERNMENT

A digital twin for Sydney

The Government of New South Wales, Australia, is creating an open-source interactive platform on which to capture and display real-time 3D data and 4D data on the urban environment.[62] The project, which enlists the help of DFSI's Spatial Services and CSIRO's Data61, aims to stimulate development in the region.[63] The twin will assist with planning in, design for and modelling of the city. The government has already demonstrated the ability to render 4D environments, with integration of live transport feeds and infrastructure building models.

The project, currently at the proof of concept stage, will eventually be publicly accessible through standard internet browsers. Industry players and government at all levels will collaborate to give users access to a wealth of information to apply in their work and lives. Meanwhile, the government will invoke applications ranging from natural disaster response, to transport scheduling, to security.

MARKETS

Energy

Can we harness digital computing power to produce real benefits in resource use and environmental protection?

JOHN BURGESS
Global Energy Skills Leader
Energy

The human race is at a crossroads on its pathway to sustainable planetary balance. Will digital technology save us from ourselves? Or will it become a negative contributor to climate change, with exponential growth of energy consumed by storage and computation?

Since the eighteenth century, energy has been synonymous with belching fossil fuel emissions which have ruined air quality wherever energy has been consumed on an industrial scale. In the past 50 years, these emissions have caused a temperature rise equivalent to one which took 150,000 years in the last major climate cycle. Hence, in the current push to wean our economies off those carbon-intense fuels, major opportunities are arising in the use of the digital twin concept to design and manage energy efficient low-to-zero carbon (LZC) solutions for buildings, communities, cities and regions.[64]

Digital twin modelling, sensing and reporting will help us to identify energy waste and nudge people to adjust their behaviour through the use of dashboarding, messaging and action tracking.

Let us look at a few examples to show how Arup are already making inroads into various phases of energy markets — from renewable energy resource discovery to offshore asset inspections, from transmission and distribution network maintenance to renewable energy grid integration, from energy storage to network resilience planning, and from energy economic policy modelling to supply- and demand-side management techniques. ▶

NETWORK OPTIMISATION FOR DISTRICT ENERGY SCHEMES

Arup is currently developing the District Information Modelling and Maintenance for Energy Reduction (DIMMER) project, concerned with the interoperability of district energy production and consumption to provide comprehensive real-time feedback about the energy impact of user behaviour.[65] The aim of the project is to achieve enduring reductions in both energy consumption and CO_2 emissions.

OFFSHORE STRUCTURES ASSET MANAGEMENT

Arup have secured a three-year partnership with EnerMech to automate offshore platform inspections. Our digital approach (Arup Inspect MInteg; AIM™) significantly reduces the time and cost spent undertaking mandatory inspections.[66] It gives operators and asset owners instant access to interactive inspection data at any time, allowing them to make informed decisions about repairs, replacements or improvements.

RENEWABLE ENERGY GENERATION RESOURCE MAPPING

Arup have produced a 'pumped hydro roadmap' for the government of New South Wales, Australia.[67] Pumped hydro is a way of storing energy by pumping water between two reservoirs — when the energy demand is low, water is pumped from the lower reservoir to the higher one. When the demand is high, water is released back through the pumps, which causes turbines to generate electricity that can then be released into the grid. A digital twin of the reservoirs is being considered as one of the technologies to monitor the operational stages.

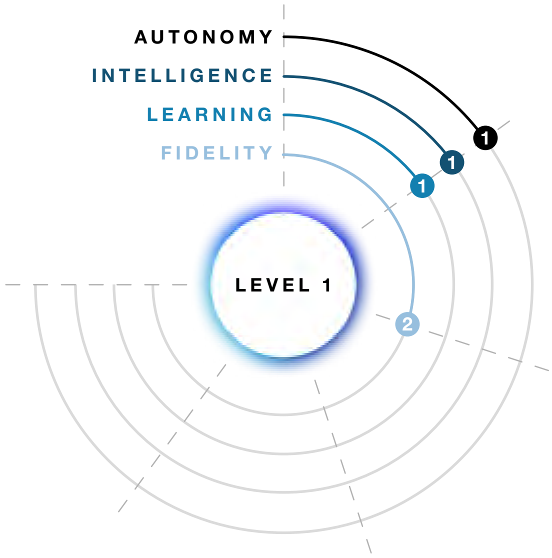
ELECTRIC VEHICLE CHARGING GRID

Arup have created a proprietary model that combines socio-economic, housing, and transport data with electric vehicle (EV) adoption rates and vehicle performance data.[68] This information is brought together to provide a detailed picture of EV charging demand through the day, across an entire city. With the uptake of EV, we are exploring the possibility of a digital twin to capture real-time charging demand, charge point placement and grid capacity. This will allow us to test different scenarios and and to understand how many charging points are needed, the likely mix of vehicles and the projected energy demand across the network.

Arup continues to invest substantial time and effort in R&D activities to expand our abilities in energy engineering advisory services. Our teams are successfully harnessing the digital twin concept across the broad spectrum of our energy interests, in order to shape a better world. ■

CASE STUDY: ARUP HOUSTON

A digitised workflow for offshore inspection



INTRODUCTION

A modern digital twin comprehends its input — inspection results, design information, condition monitoring and so on — using data analytics and machine learning. The inputs and outputs are stored in a database which should ideally feed a 3D model-based front-end application used to communicate data and analysis results about an asset to its operator. The digitised asset can be used to gain insight about the full sweep of operational data for that asset — everything from the environmental conditions within a building to the response of an offshore wind turbine to environmental loading.

AIM (Arup Inspect-MInteg) is a digitised workflow for oil and gas asset inspection.[69] At the workflow's core is a tablet application for the recording of inspection data based on the AIM tablet application, which was the first of its kind. The AIM tablet application was developed within Arup over a five-year period, and has been used in a variety of industries for improving inspection efficiency.

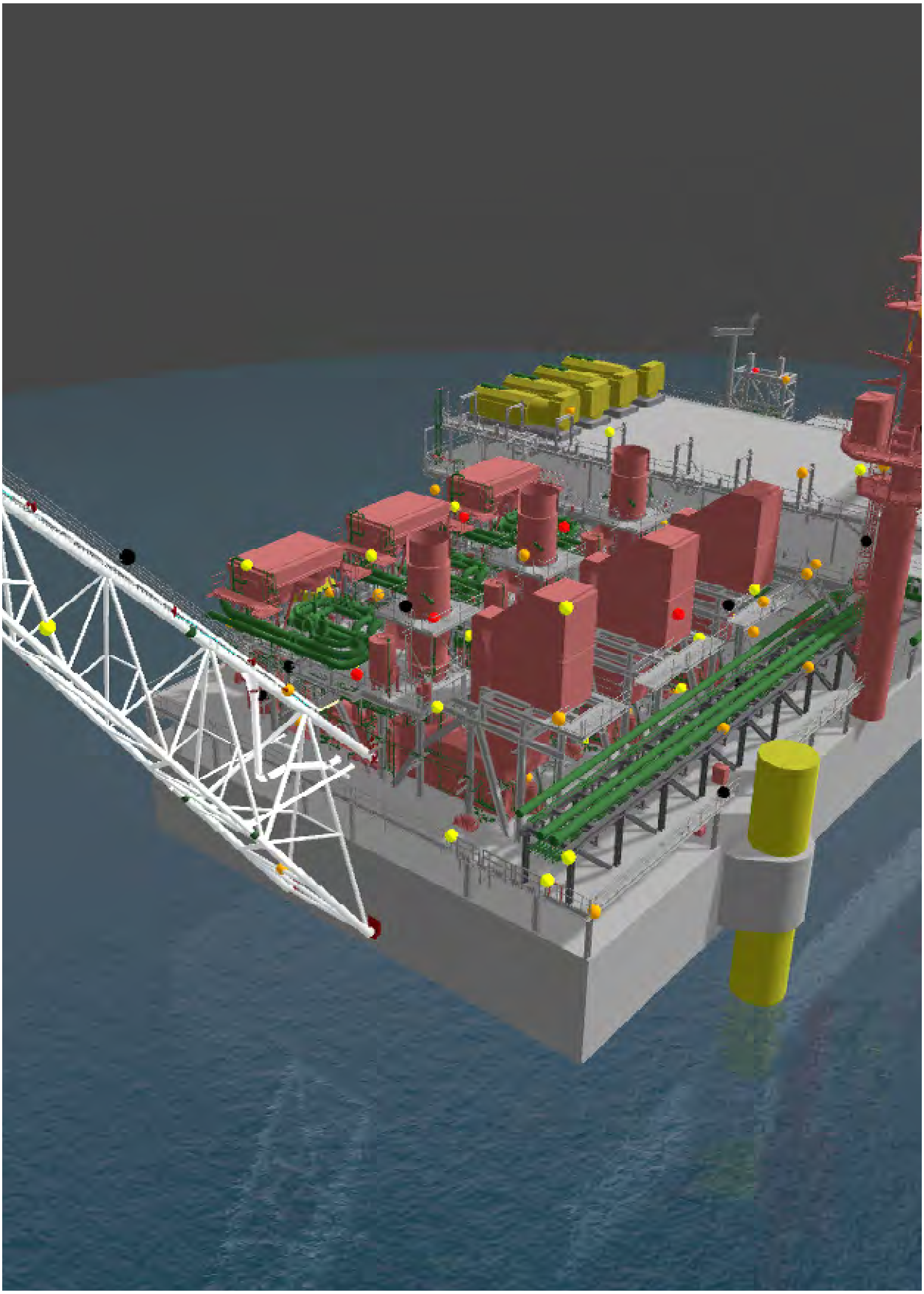
ARUP INSPECT-MINTEG (AIM)

Arup has collaborated with an industrial rope access inspection and non-destructive testing contractor, MInteg, to introduce AIM to the oil and gas industries (Figure 13). MInteg carries out onsite inspection, surveying and data collection, while Arup is responsible for data management. This includes provision of the tablet-based inspection application for MInteg to use in the field.

Integrity issues must be properly understood by qualitative or quantitative analysis of the effects of degradation found. We are currently developing a module within the AIM tablet application that visualises structural analysis results. The next step is to provide clients access to this module, on top of the existing inspection data review functionality, so that clients can visualise in one place how degradation affects the structural design performance of their assets.

GETTING BETTER DATA AND USING DATA BETTER

With AIM, data is captured on the tablet at the point of inspection, rather than by the traditional pen-and-paper method. Where wireless connectivity is available, tablets synchronise with the cloud. Hence, multiple tablets can be used at once to capture data on a single asset. Inspection includes photography, the recording of conditions, and noting comments. Photographs can either be captured on ▶



▲

FIGURE 13

Top

A screenshot from an AIM tablet application the tablet and automatically tagged to the model, or an external camera used to incorporate images into the application later on. Inspection condition observations are recorded directly on the tablet. Other data such as 360° panoramic images or laser scan point cloud data can be appended to the asset model afterwards.

DEMOCRATISED DATA

Once the data is uploaded to the cloud, the office-based client can access it in near-real-time using a desktop version of the application. Normally the asset owner/operator receives relatively sparse information during the inspection, with only a terse report and limited context around any issues. The client must then attempt to infer the inspectors' tacit knowledge to fully understand the inspection results, and to make use of them. The AIM tablet application represents an improvement on this situation, by providing clear, constant information on asset status.

PRESENT AND FUTURE DATA QUALITY

Traditional inspection is inherently subjective. Arup Inspect 3D attains consistency by limiting free text input to an absolute minimum. Data is instead entered using drop-down lists. The combination of the tablet application and and our 'Street View'-like panoramas dramatically improves the onshore integrity engineer's ability to query the data.

PARSING HISTORICAL DATA

Using innovative machine learning and data analysis techniques, Arup can parse historical data contained in both vector and raster PDFs (either newly or historically scanned), as well as in Word or Excel files. This data can be added to the AIM model to create a record of historical inspections. The intention is to liberate the value of historical inspection data, and to make it maximally compatible with data newly captured by the tablet application. The AIM tablet application can also store historical data in easily retrievable documents.

EXISTING SYSTEMS

The AIM tablet application is compatible with existing systems, which is often an important desideratum for our clients. We can, for example, automate the process of exporting inspection findings into a format suitable for an existing anomaly database. AIM is hence lightweight, in that it can be integrated into an existing workflow or management system without replacing it entirely.

TIME ON TOOLS

Conveying inspection results to clients traditionally requires inspectors to take notes by hand, and later to type up those notes. However, the AIM tablet application can automatically export reports, including all relevant inspection data, removing the need for the inspector to touch a computer and thus maximising potential inspection time. We estimate based on recent projects that the AIM tablet application, with its user-friendly interface, can save up to 25% on inspection times compared with traditional approaches.

NEXT STEPS

We are in the process of incorporating further elements into the AIM workflow, and the AIM tablet in particular.In the medium term, we plan to visualise structural health monitoring data tagged to relevant locations on the 3D model, to give a complete picture of current structural performance as against design intent. We are also expanding AIM to other safety-critical offshore systems, such as pressure systems. By applying a deep learning layer to the back end, we will automatically screen the images received from the inspections for defects or degradation such as corrosion in a first pass, and flag these to the responsible engineer as priorities for review. ■

MEET THE TEAM

BRYAN HORTON
Senior Engineer

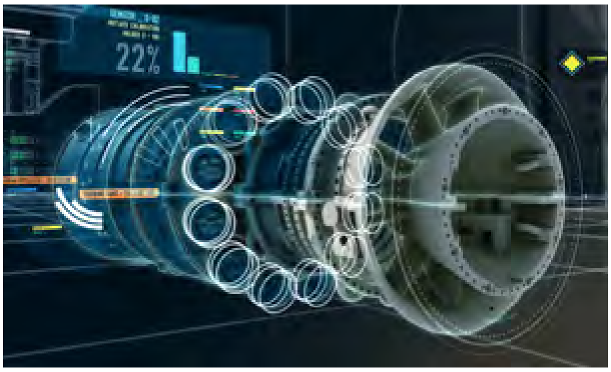
NATHAN LENNOX
Designer

TODD GRICE
Senior Engineer

CAMERON DUNN
Associate

FIGURE 14
Top
Inspector at MInteg using the AIM tablet

FIGURE 15
Bottom
An off-site oil rig project



GENERAL ELECTRIC

For the digital power plant

GE offer solutions for the continuous optimisation of power plants using digital twins.[70] The twin represents aspects of the physical asset or larger system using thermal, mechanical, electrical, chemical, fluid dynamic, material, economic and statistical data from the plant, allowing operators to predict performance, evaluate different scenarios, understand trade-offs and operate at appropriate levels of risk. GE's solution runs on the industrial platform Predix™, which ingests data wholesale and implements analytical models which can be tailored to the needs of executives and managers to interact with the plant in real-time. In this way, dispatch, efficiency, startup and asset life can all be optimised.

GE's digital twins are integrated globally, to provide them with over 44,000 operating hours of data each day from gas turbines, steam turbines and generators. This provides a glut of information to inform anomaly detection software and to prevent forced outages or damage to parts, reducing loss and maintenance costs in the whole asset. This all adds up to a comprehensive package for assisting and maximising plant functionality and balancing needs with wants, giving operators comprehensibility and visibility — despite the complexity of plant operation — in their decision making.

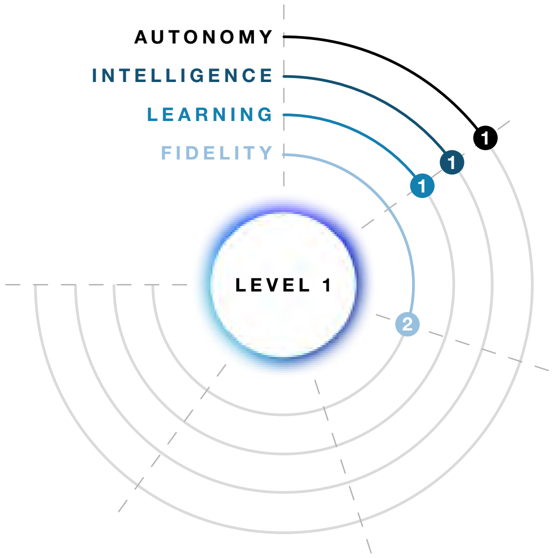
AGILITY3, BRUNEL UNIVERSITY LONDON, DASHBOARD, ESI & TWI

Lowering wind turbine O&M costs

Agility3, Brunel University London, Dashboard, ESI and The Welding Institute (TWI) are collaborating on the WindTwin project, developed specifically for the wind turbine industry.[71] It aims to solve the problem of growing maintenance and operational costs associated with running wind turbines. The consortium has developed and integrated enabling technologies that include high-performance cloud computing, system fault and degradation modelling, data analytics and visualisation for predictive maintenance of wind turbines. A sensor network system, using optimised signal processing and condition monitoring algorithms, is applied to the live wind turbine to collect operational data which will then interface with a replica, virtual 3D model, or digital twin, of the wind turbine. This collated and processed data provides a description of the wind turbine's dynamic behaviour, and physical state during real-time operations. Wind farm operators will be able to diagnose performance variations down to the level of constituent individual components, allowing them to predict failure and plan maintenance, reducing costs and downtime.

CASE STUDY: ARUP TOKYO

IoT Office — enhancing office well-being



BACKGROUND AND MOTIVATION

Recent developments in IoT technology have led to the accumulation of more detailed and more voluminous data. The Arup Tokyo office, with an area of approximately 700m^2, has recently been outfitted with 12 environmental sensors and 16 human count sensors to cover meeting rooms, private rooms, and open space (Figure 16). In addition, an AI camera and emotion analysis device have both been installed in an open space used for various events. We named this 3D-printed device the ‘penguin sensor’ (Figure 17).

Our environmental and penguin sensors taking readings every five minutes. Meanwhile, a further sensor measures people count every minute. All data is sent to a single cloud database (InfluxDB), and visualised using a dashboard.[72] This dashboard is displayed on a monitor installed at the office entrance, giving a rapid real-time overview of office status.

Our commercial environmental sensors measure temperature, humidity, CO_2 concentration, and noise level. A further movement sensor detects the number of people within the sensing area using an infrared camera. The penguin sensor, developed in-house, comprises a Raspberry Pi linked to a camera and a microphone. The camera feed is analysed by the onboard neural network to yield a real-time headcount. Simultaneously, we can record voice data from those in the vicinity, analyse that data with a commercial cloud service, and finally classify sections of speech by their emotional characteristics.

DERIVING VALUE FROM DATA

We first discovered that temperature and degree of usage between various areas of the office varied widely. To communicate the current state of the office environment in real-time, we installed a monitor at the entrance (Figure 18). This installation resulted in staff more easily being able to identify malfunctioning air conditioning, for example.

AI has recently begun playing a prominent role in our use of the office data. We took measurements of temperature, humidity, CO_2 concentration, and human count in our meetings rooms, before analysing correlations between all variables. We found, for example, that CO_2 concentration and the number of people are highly correlated (Figure 21). Using our results, we are now working to improve prediction accuracy for each variable (Figure 19).

AI also plays a prominent role in our use of the office data. For example, CO_2 data is highly correlated with number of people for each day of the week. At the ▶

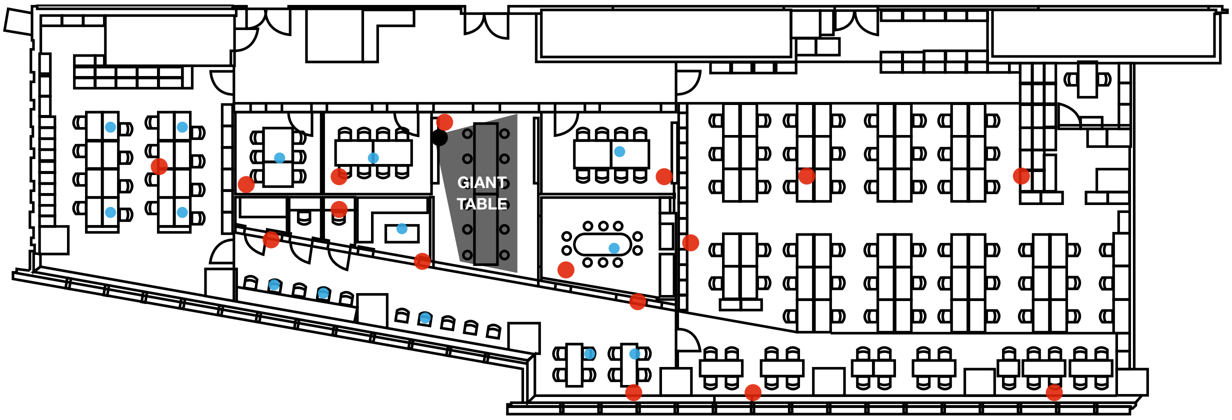


FIGURE 16
Above
Layout of the Arup office in Tokyo

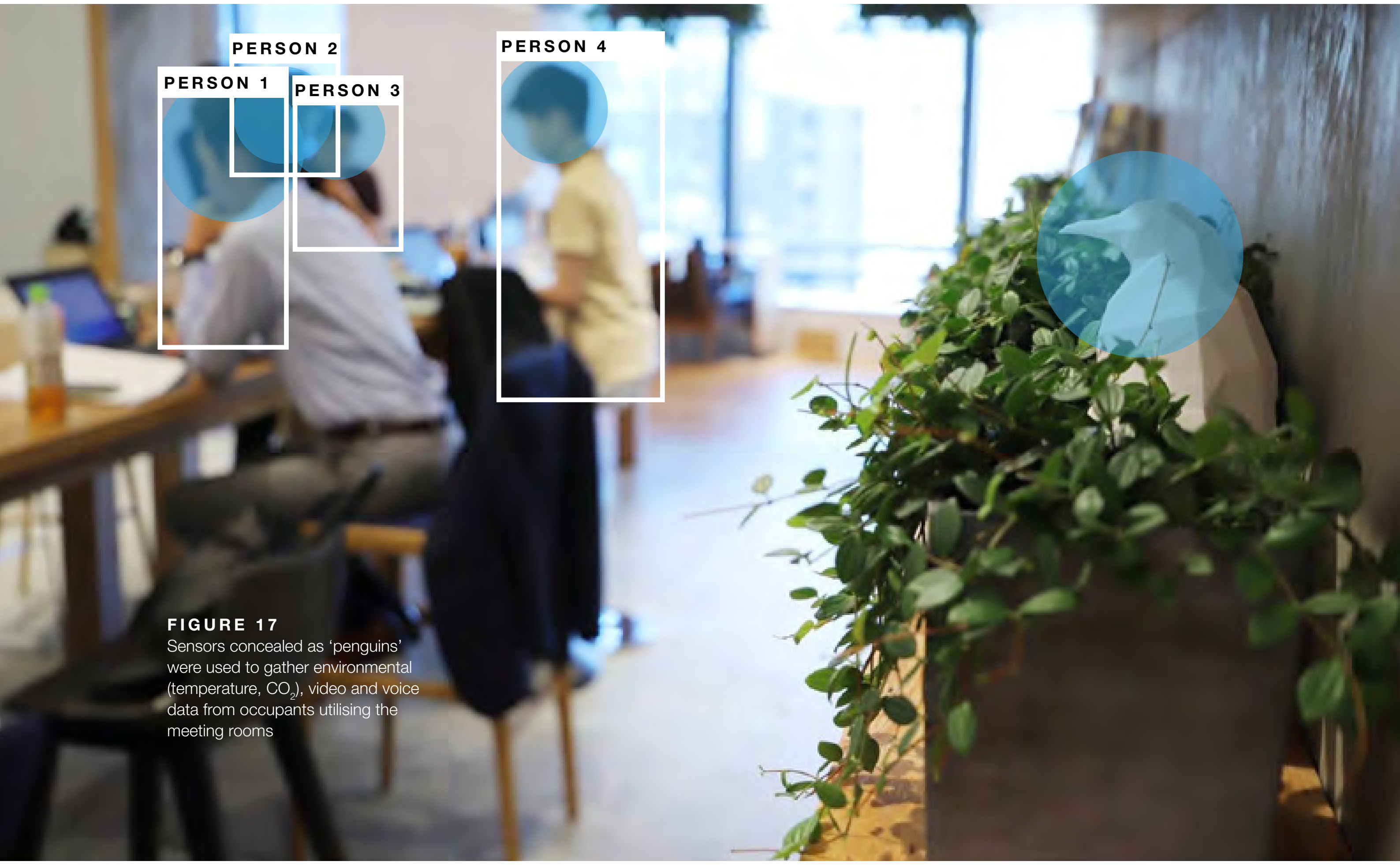


FIGURE 17
Sensors concealed as 'penguins' were used to gather environmental (temperature, CO_2), video and voice data from occupants utilising the meeting rooms

FIGURE 18

Opposite right

Real-time monitoring of sensor fluctuations in the Tokyo office

FIGURE 19

Below

Temperature and CO_2 concentration measurements of the Tokyo office

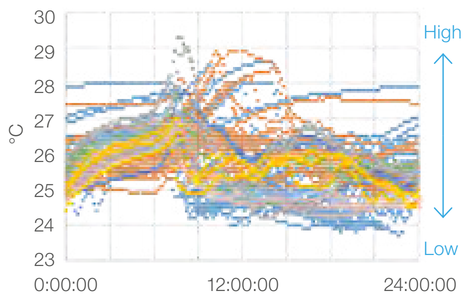
beginning of the week, there is an upward trend in the office hours with two spikes in the afternoon, but the shape of this upward trend changes with each day of the week. Closer to the weekend, CO_2 concentration can be further related to both staff who leave the office immediately after working hours and staff who work overtime, or who stay later to socialise.

Various measurements have been conducted in addition to those focusing on the office environment. For instance, we introduced AI to classify human emotions based on voice data, and analysed the results from different events. Lecture-type events show little emotional change. On the other hand, for party-type events, we observed positive emotions initially, followed by a gradual rise in anger (Figure 24). It is likely that anger per se is not the true underlying cause, but rather more enthusiastic communication styles as the night unfolds.

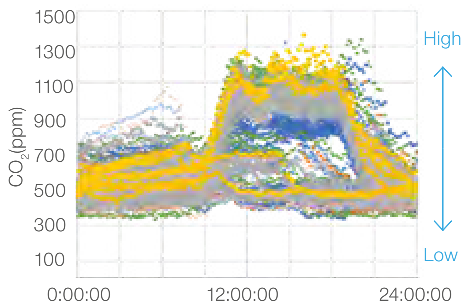
NEXT STEPS

The Tokyo office continues to conduct various trials. For example, pupillometry has been used to gauge employee concentration levels, while stress level has been estimated from heart rate fluctuations. There are teething problems: for instance, concentration levels were significantly underestimated during creative meetings and talks. We think it is important to test and evaluate continuously in the service of shaping a workplace where staff can work creatively and happily. We expect our continued testing to bear further fruit in the near future. ■

Temperature changes [°C] (measurement data from August 1st to 31st is overlaid and displayed)



CO_2 concentration changes (measurement data from August 1st to 31st is overlaid and displayed)

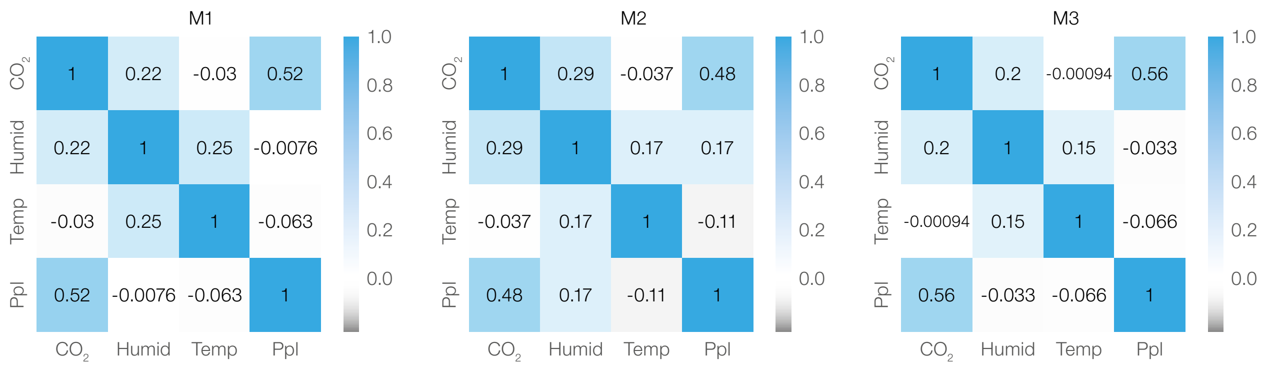


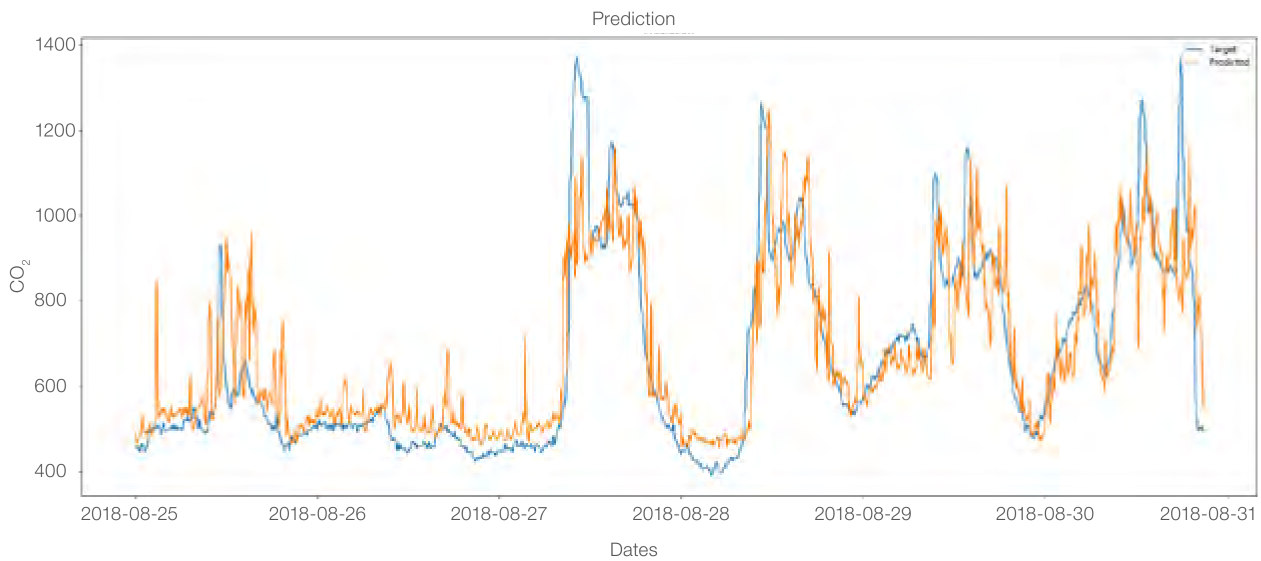

Digital Twin of Tokyo Office.
09:32:55
518
545
717
ARUP
Contact us:
HKG.KnowledgeCentre@arup.com
Knowledge Centre
Jewish Museum, Warsaw
Client
Museum of The History of Polish Jews
Scope of Services
• Hostile vehicle mitigation
• Electronic security

FIGURE 20
Right
Conference room in Arup Tokyo

FIGURE 21
Below
Correlations between the measured variables in the conference room

FIGURE 22
Bottom
Target vs. measured CO_2 concentrations in the conference room





MEET THE TEAM

KENTARO SUGA
Associate

DAISUKE KAWAHARA
Engineer

HARUTAKA OE
Engineer

KENJI LIMURA
Engineer

YOSUKE KOMAI
Engineer

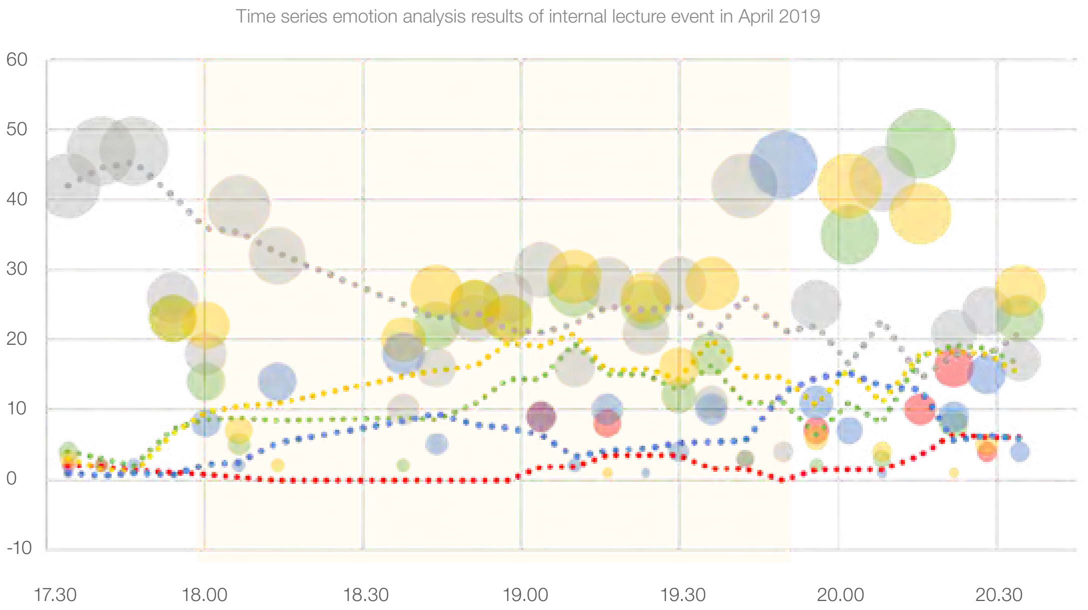
ATSUSHI MIYAZAKI
Project Manager

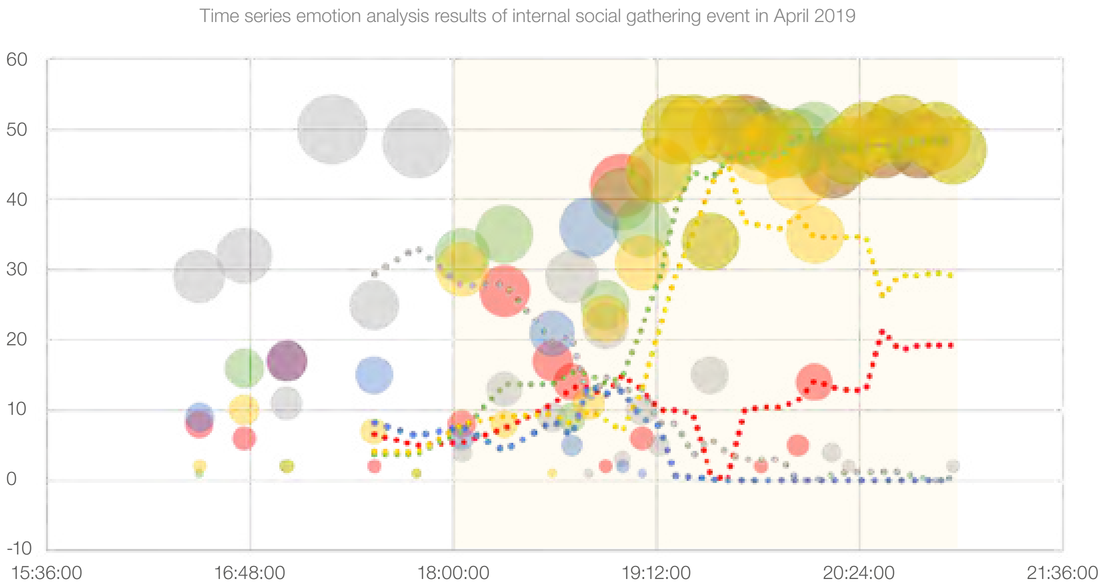
◂

FIGURE 23
Opposite
Arup, Tokyo office

▾

FIGURE 24
Below
Voice-based emotion analyses of two office events

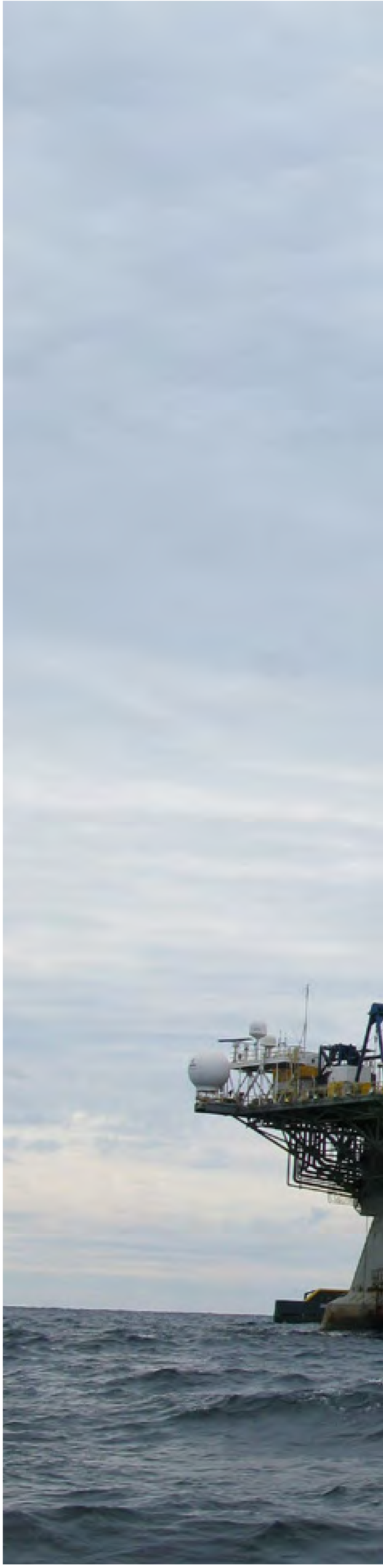




AVEVA

Savings for oil wells using digital twins

Block 18 is a group of undersea oil wells operated by BP, off the coast of Angola.[77] It was one of the earliest projects to use AVEVA NET for the handover of engineering and facility documentation. AVEVA NET aggregates engineering and asset information and makes it accessible from a single application. Tag data from documents and drawings can be automatically extracted and linked to an information model of the digital asset. Several major contractors were involved in the project and as first oil approached, information from all parties had to be collected and verified. Approximately 160,000 tags — individual component identification numbers, 2,550,000 tag attributes and 180,000 documents — made up the data.[78] Cross-referencing documents to confirm the engineering information associated with each tag would have been an arduous clerical task. Using AVEVA NET, 96% of tags were captured before first oil, as opposed to 65% using the traditional process. AVEVA NET's digital twin for handover enabled a 25% reduction of engineering man-hours, a 5% reduction in the cost of major equipment thanks to streamlined documentation, a 10% reduction in commissioning costs through better access to documentation, and a 10% reduction in operational and maintenance services thanks to the reduced need for site surveys.



Property

Realising the ambitions of a digital twins for buildings will come from embracing a framework of continuous improvement and adopting an iterative approach to identifying and exploring use cases.

MICHAEL STYCH
Director
Arup London

The construction industry is evolving rapidly, with unprecedented investment in technology set to transform the way buildings are constructed, used and maintained. The digital twin concept is one prominent vehicle for the industry to realise this transformation.

The argument for having a digital twin of a built asset is compelling — a virtual copy with which to hone design and construction performance, optimise the use of materials, improve user experience, and predict component maintenance and replacement. However, buildings are a mosaic of many parts sourced in a fragmented way, and so unlike the twin of a single component (a pump, a window), the proposal can quickly become overwhelming unless one concentrates on the value of specific outcomes. In other words, while it is technically possible to construct a twin of any building, it is easy to call into question the effort and expense of doing so without a clear value proposition.

It is likely, then, that success will only come from conceptualising digital twins as a framework of continuous improvement and exploration. There are two key principles to this idea. First, twin development must be seen as a foundational aspect of the development of everyday processes and systems. Second, we must adopt an iterative and experimental approach to identifying and exploring use cases.

A digital twin for a building should ideally be a by-product of the existing processes of design, procurement, construction and operations. Using well-structured design models taken through to completion while taking a consistent approach to data will provide a solid foundation for any digital twin. To do this, it is important to conceive of data ►

apart from the specific software with which it has been processed, so that it can be shared and understood regardless of its source.

> In property, success in any use case relies on being able to integrate data from the various interested parties (builders, owners, managers), to enable effective analysis and avoid rebuilding basic requirements each time.

Digital twins must, therefore, adhere to common data standards so that businesses and buildings can adapt to changing technological infrastructure.

IN PRACTICE

At our London office we have created a real-time data-, analytics- and application-ready digital twin, which forms the foundation of our Property Insight platform. The team started with the question of how to optimise the use of an eight-person meeting room. We trialled different technologies alongside existing installed systems, and integrated data such as room calendar booking information. This quickly revealed that the room was underused, providing evidence on which to act on and which could be extended with other rooms.

Automating the retrieval of data from various relevant systems eventually resulted in a structured data environment covering the entire building. This included the integration of BIM data for rooms as well as for individual devices. Starting from this single use case with simple visualisations, we have developed a system which allows the FM team to make informed decision on building performance and space usage.

We are currently extending this approach to an entire portfolio, working with a property developer on a programme to develop digital services for tenants. As a proof of concept, we first gave tenants control of their local lighting and temperature conditions. While this is a relatively restricted functionality, choosing this use case allows us to test interaction with a wide range of building components from different systems. This initial step has provided positive answers to questions of scaling, integration of legacy systems and asset databases. Such by-products provide insight into occupancy patterns and building performance previously not easily accessible by operators. As geometric and asset data is brought in from BIM, we are seeing the digital twin idea become a reality, not only for a single building, but for an entire, data-enabled portfolio.

Optimising design using computational analysis is normal practice, and we now have easy access to sophisticated techniques across multiple disciplines. However, with our development of a prototype building for the White Collar Factory in London, we demonstrated the potential for operation data as instantiated in a digital twin to influence design.[75] This project took a novel approach to ventilation and cooling, using an approach thus far untested in the London market, which resulted in the construction of a 200m² prototype.

We integrated separate systems and their associated devices into a real-time database, which was mapped to independent monitoring of environmental conditions to feed a predictive model. This allowed the building designers to experiment with the physical and virtual environments to optimise the design for the ventilation and cooling control systems, as well as to optimise the facade design, improving daylighting while maintaining the solar shading requirements. Having a well-organised BIM model and operational data has allowed for direct improvement to the design of the main building, all while taking an agnostic approach to systems selection and data.

The potential for digital twin thinking to transform design and construction, as well as user experience and operational efficiency, is an exciting prospect. The examples described here, along with the more extensive case studies elsewhere in this publication, start to demonstrate the capacity of digital twins. They show that by adopting an iterative approach while developing solid foundations for digital twins, we can achieve the longer-term goal of widespread adoption by the property industry. ■

QUESTION AND ANSWER

Our mission is therefore not merely to liberate data, but to filter it. Our job is to extract meaning from the noise. To turn data into insight and insight into action.

JOSHUA RIDLEY
CEO and Co-Founder
Willow

CAN YOU INTRODUCE WILLOW FOR US?

Willow is the digital twin for the built world. We are a technology company revolutionising the way we design, build, operate and interact with the built environment. Through our software and services, we are converting bricks-and-mortar assets into living, learning, evolving digital twins.

CAN YOU TELL US ABOUT YOUR JOURNEY WITH DIGITAL TWINS?

Willow's origins were in the design and construction of complex projects. We were an early adopter of BIMs, and it was a natural progression for us to move from BIM to digital twins. Once a BIM has been generated, it makes sense to convert it into a digital twin by enriching the model with both static and live data. This includes the asset register, maintenance logs, warranties and O&M manuals — as well as live data from the building management system.

Today, we have an entire arm of our business, WillowDigital™, which works at the design and construction phase of a building's life to enable its digital twin.[76] This expertise in digital architecture, digital engineering and information structuring allows Willow to introduce digital twins to the building owner very early in the project. This allows Willow to shape the client's digital and technical requirements prior to the builder being appointed; we work throughout the supply chain to deliver on this strategy. This part of our business feeds directly into our software platform, WillowTwin™, to ensure that at the end of construction we have the basis of a digital twin.

WHAT ARE THE PAIN POINTS YOU'RE ADDRESSING?

For the owners of real estate, the management of building data is a huge pain. Every day, the built environment produces huge amounts of data, from the occupants who walk the corridors, to the equipment that powers and measures operations. Sadly, most of this valuable information goes to waste, lost in fragmented digital forms that are locked away in proprietary systems. The mismanagement of this data has a negative impact on bottom line performance, and owners are throwing away inestimable amounts of untapped value.

The real estate industry has historically struggled to embrace technological innovation. Major providers have fallen short in their ability to remain adaptable for future needs. This means that owners have zero data ownership, their information is isolated in the systems of individual buildings, and they face the threat of cyber breaches or great financial cost every time they introduce a new technology at scale.

Our customers receive so much data that they feel overwhelmed and distracted. As Yuval Harari put it in *Homo Deus: A Brief History of Tomorrow:* "In the past, having power meant having access to data.[77] Today, having power means knowing what to ignore." Our mission is therefore not merely to liberate data, but to filter it. Our job is to extract meaning from the noise. To turn data into insight and insight into action. In doing so, we are making what came before us seem outdated, clunky, inefficient, costly and painful.

WHO OWNS THIS DATA?

It's a very interesting question: of course, we need legal clarity on who is the rightful owner of the data. The approach thus far has simply been that whoever owns the building owns any data gathered within it. But it's not that simple; just think of the example of tenants with medical patients whose data may be highly sensitive.

I believe in a free world, in which we empower people to make the world better, to have better experiences. I wouldn't want technology to be used for anything other than that purpose. We want users to have a better experience, and we want owners to be able to deliver a better experience. How this is implemented in a hospital as opposed to a high-rise building, though, may differ. This is a question that has to be answered on a case-by-case basis, but with the user-centred philosophy in mind.

WHAT ARE THE BENEFITS OF HAVING ACCESS TO THIS KIND OF DATA?

Digital twins can increase the value of real assets in a number of ways. We estimate that a 15–20% reduction in variable operating costs for office buildings is possible. This reduction comes courtesy of big data analytics, improved visibility for facility managers, optimised enforcement of warranties, predictive maintenance, automated compliance with fire and safety regulations and energy optimisation algorithms, as well as reductions in machinery downtime.

Additional benefits include an estimated 10–15% improvement in tenant retention for office and industrial assets through enhanced tenant feedback on building performance, more timely processing of tenant service requests, and improved visibility of the performance of facility managers. Organisations also see benefits from big data analytics of space utilisation, use patterns, occupation growth, merger/acquisition and key personnel changes in relation to the office and industrial tenants. ▶

> We estimate that a 15–20% reduction in variable operating costs for office buildings is possible.

FIGURE 25
Above
Willow's digital twin for tenants

WHY DO OWNERS NEED DIGITAL TWINS?

Digital twins promote better decision making across an organisation. With WillowRail, our rail maintenance platform, we gather and integrate hundreds of sources of data from individual proprietary systems to provide a single view of a rail network, unlocking new and actionable insights.[78] This brings benefits to all levels of the business, from the CEO to Asset Managers and maintenance teams, all in real-time. Through WillowRail, the organisation now has a single source of truth in a unified interface across their business. Accurate decisions can be made in shorter times, based on a complete picture of the problem. The platform has the power to upskill and empower the workplace by providing access to richer information.

Digital twins are also key to driving savings throughout the building lifecycle. Asset owners are having to spend more each year to operate and maintain their assets. For an average-sized building of 500,000 sq. ft, asset owners are required to spend approximately USD 2,985,000 on an annual basis on variable operating expenses, including USD 1,075,000 on building repairs and maintenance, USD 840,000 for cleaning and USD 1,070,000 for energy. On a portfolio basis, assuming a portfolio of 40 buildings, this equates to more than USD 119 million per annum of variable operating expenses. We estimate that the net saving in a building's variable operating expenses generated by WillowTwin™ equates to approximately 3–9% of variable operating expenses per annum. A reduction in variable operating expenses also leads to a substantial increase in asset valuation.

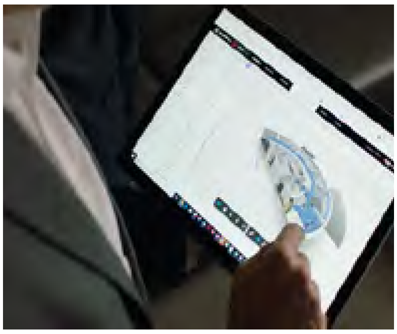


FIGURE 26
Above
Willow's digital twin platform

HOW WILL THE GROWING NUMBER OF DIGITAL TWINS AFFECT THE PROPERTY MARKET?

The demand for digital twins is fuelled by behavioural changes in occupants and owners. Occupants are demanding more from their space, accustomed as they are to extensive personalisation and customisation in other aspects of their lives (smartphones, media consumption, and even culinary choices). Owners, meanwhile, are eager to understand what is important to today's tenants and their employees, and what the future will hold.

Willow is developing a workplace application to capture tenant feedback via surveys, which will allow owners to readily stay in touch with their tenants and to measure tenant satisfaction (or otherwise) and attitudes to continued occupancy. Owners currently find this difficult to do in a cost-effective manner, as tenants tend not to prioritise the provision of such information. The manner and speed with which facility managers respond to and address customer service requests can have a significant impact on overall tenant satisfaction and tenant retention. Our applications will allow owners to survey such variables as frequency of tenant service requests, average time for closure of requests, facility managers responsible for each item, tenant satisfaction following item closure and ratings for facility managers.

Using this type of data, we can optimise the workplace, improve satisfaction with space, and increase real estate performance. Most importantly, owners will be able to anticipate change and develop timely solutions to address that change. ■

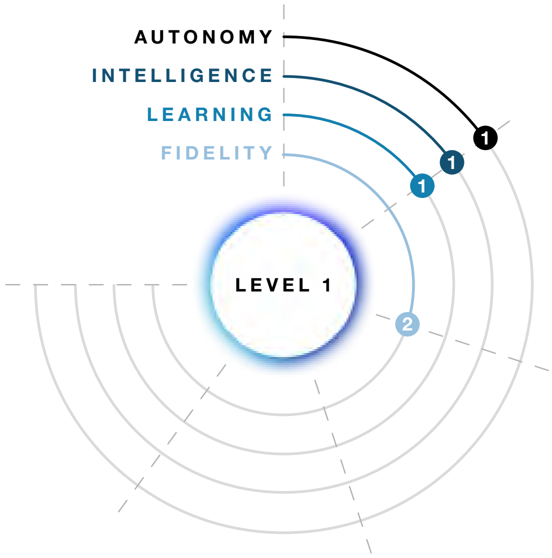
IBM'S COGNITIVE DIGITAL TWIN (IOT WATSON)

A platform for desk availability

Connected IoT devices stream vast quantities of data to the cloud, have yielded unprecedented levels of knowledge about how these systems operate in the real world. IBM's Watson® allows us to learn from these sources using powerful data modelling techniques to aggregate data into a representation that forms the backbone of a so-called 'digital thread' connecting digital twins, digital models of physical assets, and groups of assets. Watson can absorb and analyse data in virtually any format and from any source, to correlate it with other sources. Previously inaccessible insights are made possible, enabling the development of new initiatives and the rejuvenation of existing ones. Deloitte's Edge building in Holland analyses an employee's calendar and reserves the necessary desks accordingly.[79] With so much documentation stored digitally, having an assigned personal desk will become a thing of the past. The proper collection and analysis of data allows big gains in productivity and space usage to be made.

CASE STUDY: ARUP AMSTERDAM

Digital twin for the Dutch government, The Hague



PREPARING FOR VITAL COMPLEXITY

The inexorable drive towards sustainable energy usage means that in the near future, buildings will no longer be based on preprogrammed responses alone. Instead, they will need to be able to program themselves by monitoring the environment, different system states, occupancy and behaviour patterns, and then using this data to predict future states of the building. This goes far beyond what is possible with current building controls, based on solitary sensor readings. Enabling the energy transition therefore requires a new toolset, enriching sensor data with far deeper insight: a digital twin.

The twin's simulations use empirical and physics-based mathematics to model building performance, and are thereby able to mimic dynamic and complex behaviours, to increase the efficiency of the physical asset. Each digital twin represents a unique one-to-one correspondence with a physical asset. No two buildings are the same, and it is the digital twin that will provide the key capability of managing each building's particular environmental and spatial conditions, user behaviour, and state of repair.

The real power of the digital twin, however, arises from its machine learning capabilities. To reasonably predict asset failure or to detect opportunities for optimisation, a data-driven approach will require a large amount of data collected over a long period of time. By running simulations on the model, the digital twin can generate 100,000 times more data than can be provided by the sensors alone. In this way, the digital twin becomes smarter much more quickly than the unaided physical building ever would. Furthermore, a digital twin simulation can interpolate many more virtual sensors than would ever exist in reality, thereby filling the information gaps which could not be gleaned from the sensor data alone. Beyond even this advantage, the digital twin will already understand the relation between these points, whereas discovering this relation solely from real-time building data would be extremely challenging, due to the many non-linear and dynamic physical responses characteristic of the built environment.

PREPARING FOR VITAL COMPLEXITY: THE POWER OF DIGITAL TWINS

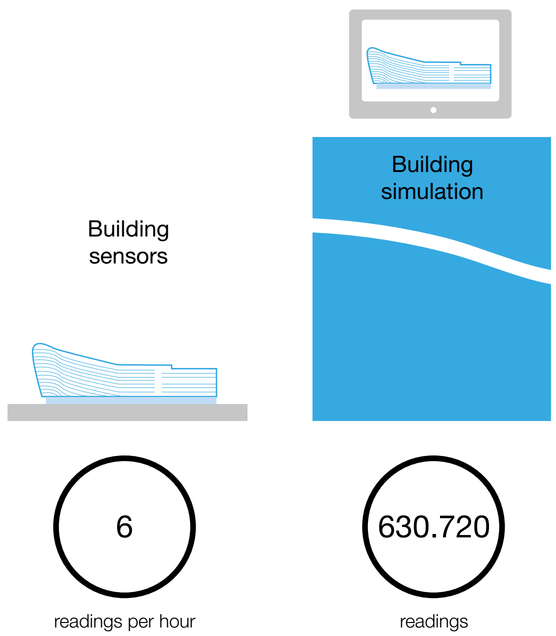
In the next decade, we foresee a large-scale integration of (decentralised) electricity production from renewable energy sources. In many countries, the the share of renewable energy sources will grow in parallel with the extensive electrification of demand, e.g. replacement of traditional cars with electrical vehicles or displacement of fossil fuel heating systems, such as gas or oil boilers, with energy-efficient heat pumps. Simultaneously, the energy supply is developing, with low-temperature district heating grids powered by various renewable sources.[80] These changes to both demand and supply impose new challenges on the management of energy systems, including, for example, the variability and limited control of energy supply from renewables or increasing daily load variations, due to the high impact of additional electricity consumption.

The changes to the grid and on implementing energy storage systems will require major investments. The more variability can be solved locally, the less influence it will have on the grid. Also, the more demand and response can be matched locally, the less the integration will require energy storage. It is expected that real-time variability management will become a major cost driver of reliable operation, which will result in variable rate structures and financial incentives at all levels of the energy network. This will require buildings to become demand responsive and energy flexible. It will also require buildings to be able to relate to their context and surrounding, forming part of a smart city. And it will require buildings that are able to base current control decisions on future projections.

DIGITAL TWIN OFFICE BUILDING, THE HAGUE

Arup is building a digital twin of the Dutch government's County Hall building in The Hague — a replica of an office building of around 16,000 square metres.[81] Over 30,000 data points from the existing Building Management System were first extracted. Next, another 350 IoT sensors were added, specifically tailored to measure user interaction. The dimensions of the physical building were translated to the virtual world through 3D scanning, and linked to a scientific simulation model which is fed the sensor data.

The province aims that all buildings should be energy-neutral by 2040.[82] The strategy is twofold: it optimises current functioning of the building, while renovating, uplifting and transitioning where needed. But, as with any other building, energy meters do not at present indicate whether the current building is over-consuming. And as with any other building, the Province House is a unique building. There is no other building of exactly the same shape, at the same location, experiencing the same weather conditions — and no building is used in exactly the same way as the Province House. There is no reference building against which to compare it. But by building a virtual twin of the building, we obtain an exact copy of the building against which to compare real-time data. ▶



◂

FIGURE 27

Left
Number of data readings in an hour from sensors as compared to the simulation for the Hague building

This reveals not only whether the building is consuming too much energy, but also how much more — and where exactly the energy leaks are to be found.

Comfort requirements specific to the digital twin, such as lighting, air quality, temperature, humidity and acoustics, are likewise linked to specific office activities. These might include meetings, working behind a desk, relaxing and focussed working. Each task comes with a specific set of preferences and needs. By mapping actual performance against comfort needs, opportunities for comfort improvement or energy savings can be ascertained.

AN ENERGY-NEUTRAL DIGITAL TWIN

By creating a digital version of the building, different alternatives for an energy-neutral county hall can be digitally simulated and tested before being implemented in real life. A better facade, more sustainable energy generation, more comfortable building services, energy exchange and storage are all part of this future version. This makes it possible to test different design alternatives in a context of the exact user interaction and specifics of the building. For example, knowing how the building heating load will be affected by future improvements to the facade can be very relevant information if part of the heating system needs replacement before the renovation takes place. Furthermore, certain system choices, or more effective and targeted building utilisation, can have such a large impact on the building energy balance that the order of effectiveness of alternative measures is changed. The projection of future scenarios with a digital twin is therefore of great help in making future investment decisions. ■

MEET THE TEAM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Director


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VERONIKA HEIDEGGER
Software Developer


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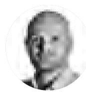
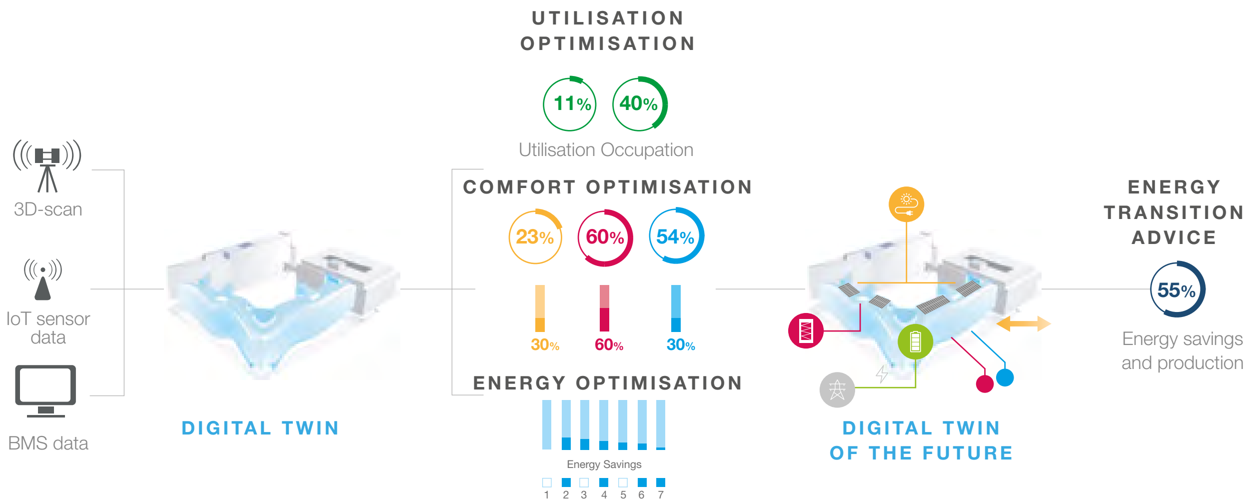
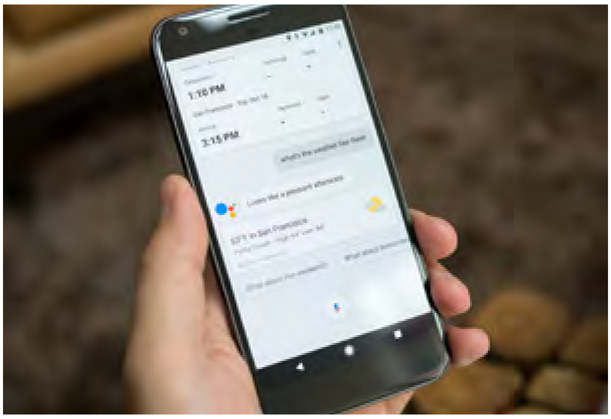

SENNO KAASJAGER
Programmer

FIGURE 28
Opposite top
The Hague's County Hall and the core components of the digital twin

FIGURE 29
Opposite bottom
The digital model for The Hague's County Hall


3D-scan
IoT sensor data
BMS data
DIGITAL TWIN
UTILISATION OPTIMISATION
11%
40%
Utilisation Occupation
COMFORT OPTIMISATION
23%
60%
54%
30%
60%
30%
ENERGY OPTIMISATION
Energy Savings
1 2 3 4 5 6 7
DIGITAL TWIN OF THE FUTURE
ENERGY TRANSITION ADVICE
55%
Energy savings and production



GOOGLE

A personalised home assistant as your digital twin

The concept of a digital twin can be extended beyond replicating a building or a physical asset. What if you replicated yourself? Google is developing its Google Assistant technology to serve as your own personal digital twin.[83] The idea behind this is ultimately to save time by carrying out the more mundane jobs for you, such as booking appointments and making calls. It can also make decisions to help improve your personal productivity and wellbeing. In the same way, a digital twin of a building will collect data about room temperature and then suggest ways that the building can be optimised to save energy. The device learns about your routines and your preferences and can then prompt you to make decisions. Instead of the information being captured through sensors in the building and then being displayed on a 3D model, speech recognition is used to collect data, enabling your device to talk to you. This example highlights the variation of forms that a digital twin can take, and the different ways in which they operate.

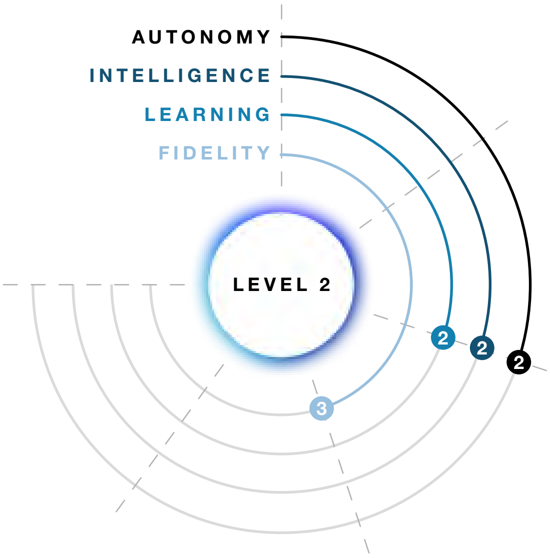
MICROSOFT & THYSSENKRUPP & WILLOW

Elevating the elevator business

Willow and Microsoft are helping ThyssenKrupp Elevators to access the vast amount of data in the central nervous system of their new innovative Test Tower in Rottweil, Germany.[84] WillowTwin™ is a virtual model of the built environment, while Microsoft's Azure Digital Twins is an IoT service that powers comprehensive virtual representations of physical environments and their associated devices, sensors, and people. Harnessing this combination, Willow and Microsoft are enabling ThyssenKrupp Elevators to create new ways to manage maintenance contracts, create personalised experiences for visitors, change the way security is managed, and ensure that their elevators are functioning at all times. The virtual tower encompasses 15,000 live data points and over 57,000 static data points — any of which can be found at the click of a button. This digital environment allows checking of system behaviour and simulations of the system and people flow analytics, getting robust results without the need for physical testing. Detection of possible failures will enable service interventions before problems even occur. This has changed the ways that Thyssen interfaces with the building — whether this involves the occupant, owner, or the operator. Their belief is that it won't be long before every building will be required to have a digital twin.

CASE STUDY: ARUP MELBOURNE

Digital twins for building tenants



INTRODUCTION

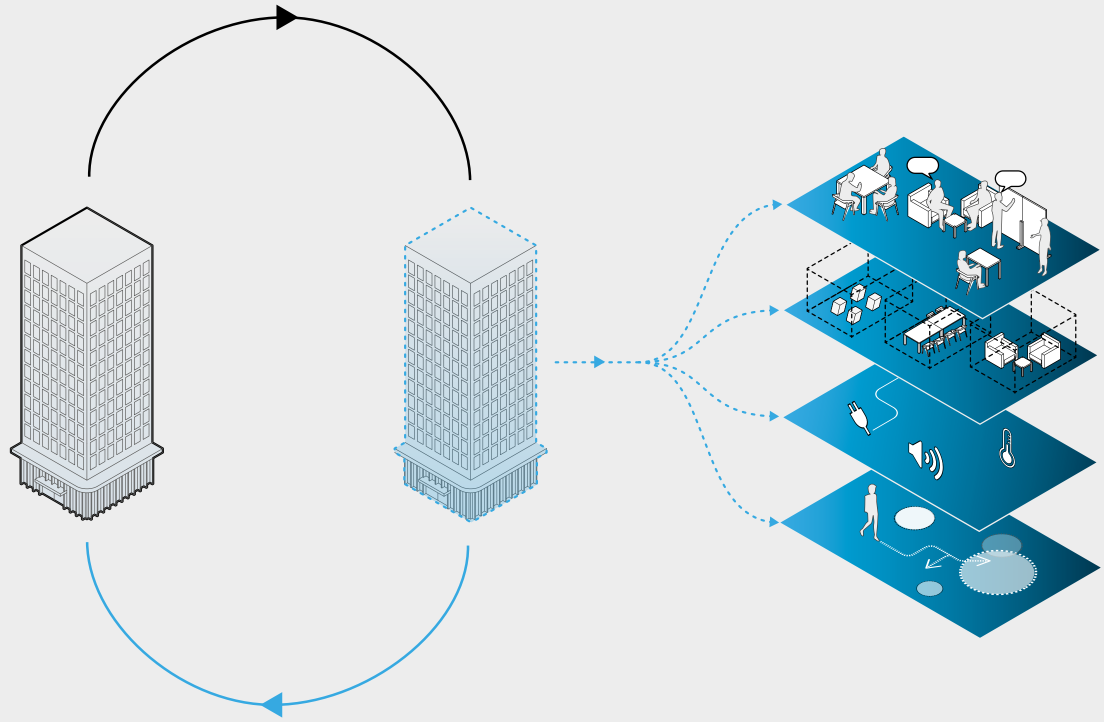
Arup Melbourne has recently moved to a new office, designed by the local team in collaboration with Hassell architects. A central element of the design from the outset was the deployment of sensors to gather data throughout their tenancy. Now settled in the office, the team is using the digital fingerprint constituted by the collected data to create a digital twin.

The digital twin initiative aims to gather real world data to simulate in digital space. Research continues to support the importance of office space design, and its link to the wellbeing and performance of the people who work there. Following the Melbourne team's recent move, it has become clear that the design and optimisation of usable space will require constant curation in order to get the best from our staff and business. The key benefits and value of this work targeted five main areas, listed below:

1. Improving Productivity
Research continues to demonstrate a close relationship between worker comfort and productivity. A recent controlled study reported a productivity deficit of 4% at cooler temperatures, and 6% at warmer ones.[85] Building on this research, the Melbourne team has developed an app to gather information on worker comfort and perceived productivity. This qualitative information helps to feed a digital twin to yield intelligent suggestions for alternate working locations and to provide user control over personalised environments. The result projected an increase of up to 11% in productivity.[86] Additionally, this functionality establishes the methodology of using AI derived from empirical evidence to inform future designs.

2. Spatial Optimisation
On average, rent constitutes 9% of business operating costs.[87,88] With the aid of a camera-and-sensor IoT network, a digital twin could ascertain current space usage. Pattern recognition could yield intelligent suggestions on how a space is optimised (e.g. through retrofitting or subleasing rooms or zones). Tenants would benefit from such insight to optomise their own use of space and expenditure. This digital harvesting methodology has the potential to expand to other typologies where the activity in the space is in flux and the need for spatial optimisation is constant. The team has identified public infrastructure, education facilities and exhibition spaces as prime candidates to apply this type of thinking and approach.

3. Energy Reduction
Approximately half of commercial energy ▶



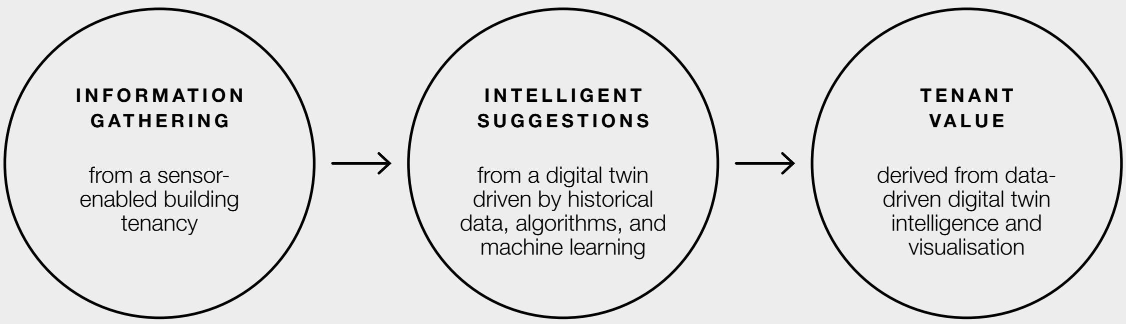


FIGURE 30

Top

A digital twin can be a feedback and monitoring opportunity to drive productivity gains, improve worker wellbeing and reduce operational costs

FIGURE 31

Bottom

The diagram schematises how value may be derived from collected data when mediated by a digital twin consumption in advanced economies is due to offices. Due to imperfect control of HVAC and lighting systems, a significant proportion of this energy is wasted maintaining unoccupied or inefficiently configured spaces. A digital twin can support efficient automation of environmental control, based on data gathered from actual usage of a space. Savings of up to 20% are projected to be made on energy costs with this kind of intelligent building management.

4. Security
The team found that the digital infrastructure provided by a digital twin lays the ground work for proactive automated security systems. This can be achieved with AI image recognition technology in the IoT network. Areas previously monitored by people could then be monitored by a digital twin, leading to a potential reduction in labour costs by up to 50%.[89] Insights from historical data could also be used for area-specific threat detection.

5. Wayfinding
Current workplace designs rely on workers' familiarity with office fitout to find their way around. Using data from 3D as-built BIM models and occupant geolocation, a digital twin can be used with an augmented reality app to guide users to free rooms, quieter or under-occupied spaces, or specific facilities. The introduction of two-way interaction systems in conjunction with wayfinding can also be used to provided adaptive and real-time way finding in a space. This type of digital twin provides facilities managers with the ability to have real-time influence over the usage of a space. This digital twin study quantifies the benefits of wayfinding tools and demonstration the extreme value in it's potential to affect time reduction and adaptive management applications. Additionally, wayfinding technology can benefit the safety of the space by using it for the identification of evacuation paths in emergencies.

KEY CHALLENGES AND OUTCOMES

The key challenges of this case study have been in data acquisition, data cleaning and communication. Due to the fragmented nature of data ownership and creation in the buildings industry, acquiring data continues to be a significant challenge. Once data is acquired, a significant proportion of time is typically spent on cleaning the data to be in a suitable format for processing. This process can take up to 80% of the component's delivery time based on industry standards. Key to successful delivery of the project was the development in creating the backend of the digital twin to handle and process a large volume of various data types from a wide range of sources. The project dealt with many data silos and stakeholders that required consistent and effective communication from technical IT infrastructure experts to general managers. We are at a crossroads, entering a new, data-driven market. The industry does not fully understand the potential value that could be derived from this technology. Navigating this space is complicated, and solutions are unique to each client. Our approach focuses on establishing projected returns on investment for a particular user group, and facilitating discussions around the value of data and digital twin infrastructure while transcending the complexity of the project.

PROJECTED RETURN ON INVESTMENT

The project has revealed a number of significant benefits delivered through the adoption of a tenancy digital twin. One of the largest observed benefits is in enhanced employee engagement, leading to reduced turnover. Employee turnovers are costly, and an increase of 2.5% of employee satisfaction can result in a high-impact reduction in overall labour turnover costs. From a productivity perspective, we are projecting performance gains of up to 10%, based on industry research, translating to up to 182 hours of performance uplift per person per year.

Additionally large revenue uplift was identified for building owners, who, when providing appropriate infrastructure to facilitate DTs can bring a more attractive product to market. Providing offices and spaces with enhanced digital infrastructure provides measurable improvement to businesses occupying them, as such rental yields of such spaces can be increased.

Given our commitment to the UN Sustainable Development Goals, energy reduction is also a key focus. With ongoing building tuning unlocked through the digital twin framework, we are projecting tenancy energy usage reductions of up to at least 20%, leading to cost reductions of at least $5 per square metre per annum. Local electricity and building services will vary from region to region, and a digital twin approach allows for simulations to suit. Measuring spatial optimisation ROI continues to be a key challenge. As the project develops, we are identifying drivers and metrics to measure and quantify investment returns for spatial optimisation.

Much of the project's findings and opportunities are now being applied to large-base building applications as well as construction sites. For example, we see value in 'micro digital twins' for bespoke construction assemblies, which can incorporate AR and VR representations of building programmes, drawings and 3D models to enable clients to mitigate risk during the construction of complex systems. This could be achieved through the provision of software platforms enabling workers to visualise and process physical tasks in the digital space, prior to procurement and construction, driving significant efficiency gains on site. ■

CONCLUSIONS

Ongoing collaboration with industry and academia is key to the digital twin project. Through our strong relationships with local universities and augmented reality experts worldwide, we have developed a cutting-edge visual platform to increase efficiency and to boost worker productivity and satisfaction.

MEET THE TEAM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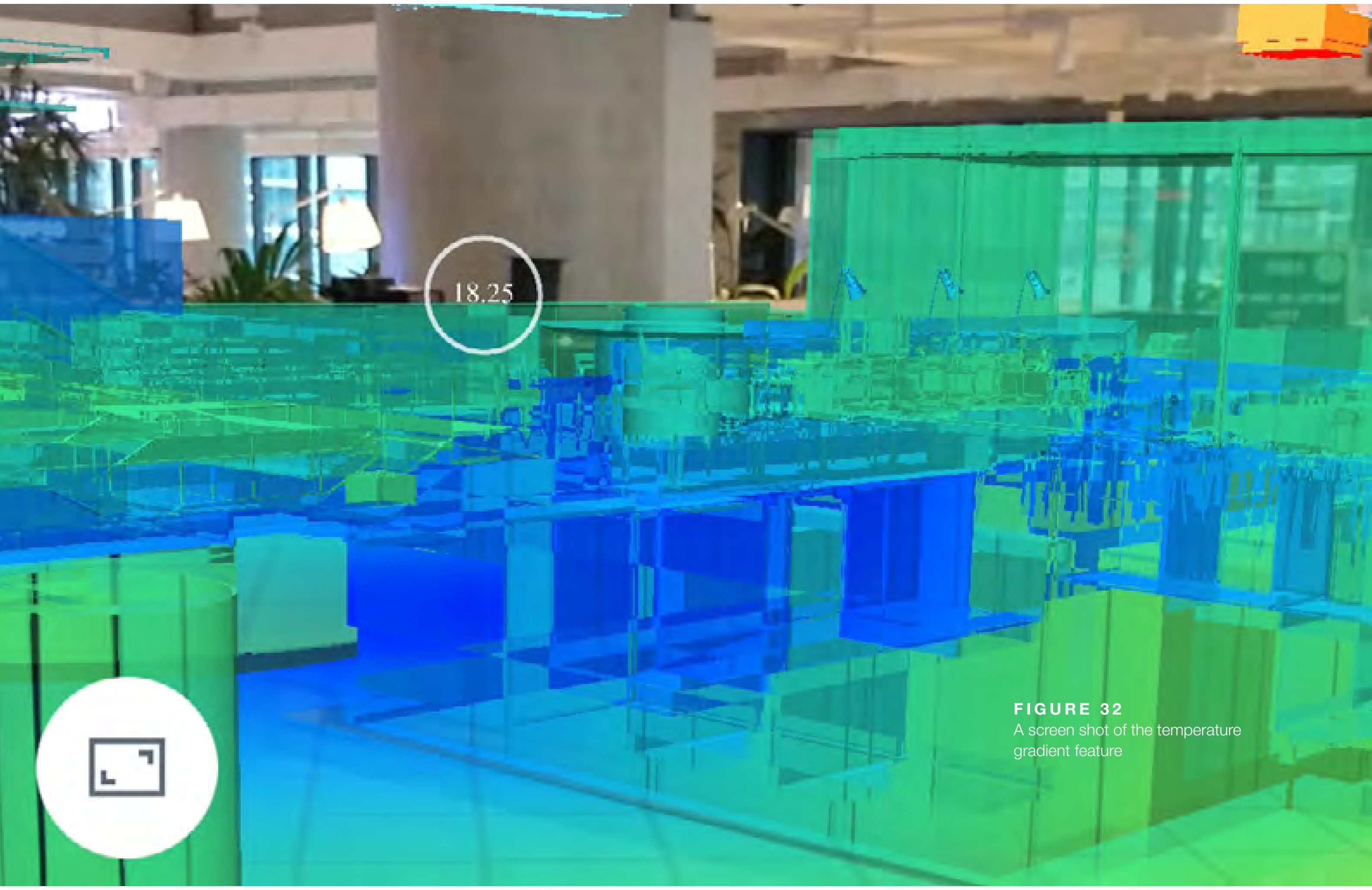
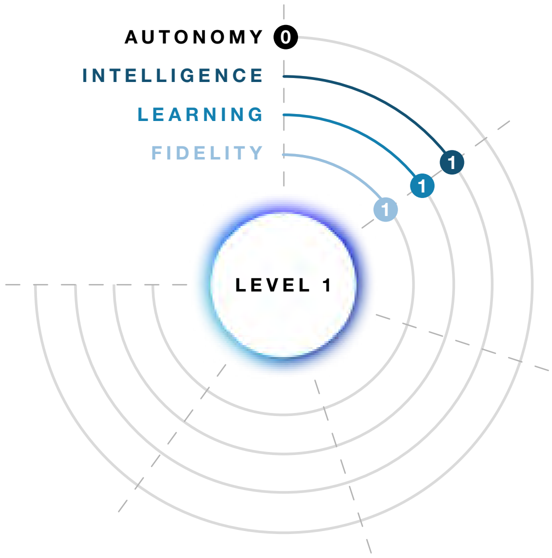


FIGURE 32
A screen shot of the temperature gradient feature

CASE STUDY: CAMBRIDGE

Digital twins for research and development facilities



BACKGROUND AND MOTIVATION

Arup is developing the entire Asset Management Service for the R&D facility of a large pharmaceutical company. The new campus is currently under construction within the UK's leading biomedical hub. The buildings and infrastructure will not only support world-leading research, but will also meet the most exacting of sustainability and energy targets. The highly regulated nature of the pharmaceutical industry means that robust information systems already exist: to support R&D processes, for example, or to track the distribution of medicine to patients. However, the legacy IT systems used to manage physical assets often make difficult or prevent the collation of information into a single view of the asset. A comprehensive digital twin of the new campus appears the optimal solution for long-term operational benefit.

SCOPE

Arup is working with the client to scope out the work for the R&D campus, to develop a system of interconnected digital twins. The overall digital twin, a system of systems, will furnish a competitive advantage, going beyond traditional R&D asset management practices. All primary asset data sources, both static and dynamic, will be integrated into this replica, enabling advanced analytics, modelling and prediction of future behaviours.

Among other advantages, this will allow deeper integration and collaboration at each point along the asset management supply chain, in an economically efficient manner. Successful service delivery on campus will thus depend on the creation and maintenance of a digital twin, or asset information model, capable of real-time behavioural responses and prediction according to its surrounding ecosystem. The campus digital twin will play a key role in ensuring the highest standards of safety, customer service and asset sustainability. It will enable the successful delivery of services, such as lifecycle planning, facility and laboratory maintenance, energy and utilities, provision of scientific services, delivery of capital portfolio projects, and building monitoring and control.

Arup and their client have worked closely to determine how customer needs can best be met through the appropriate use of technology and of asset data. This was supported by an analysis of the client's IT and data landscape emerging from the physical build of the R&D centre. We then looked at several scenarios comparing the positive ▶

INFORMATION HANDLING	SYSTEM SOLUTION	ADVANCED INSIGHT
Collect	Integration to single truth	Data enrichment
Control and validate	Centralised catalogue	Business analytics
Maintain	Maintenance management	Advanced analytics
Share	User visualisation	

TABLE 6
Top
Capability blocks of the digital twin

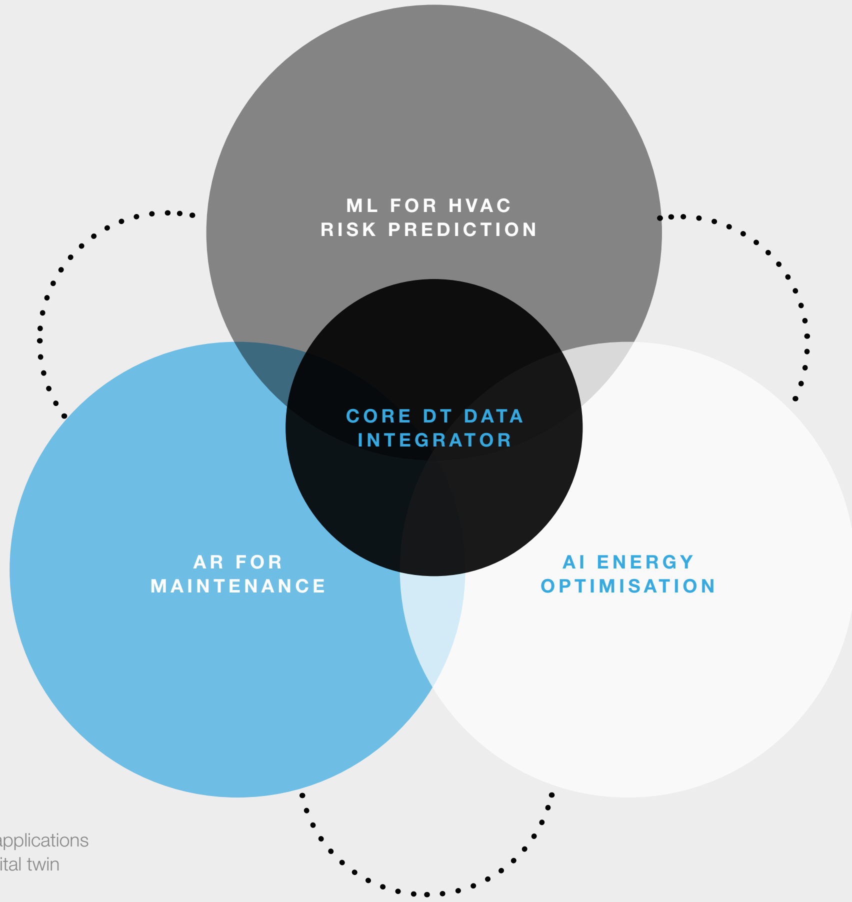
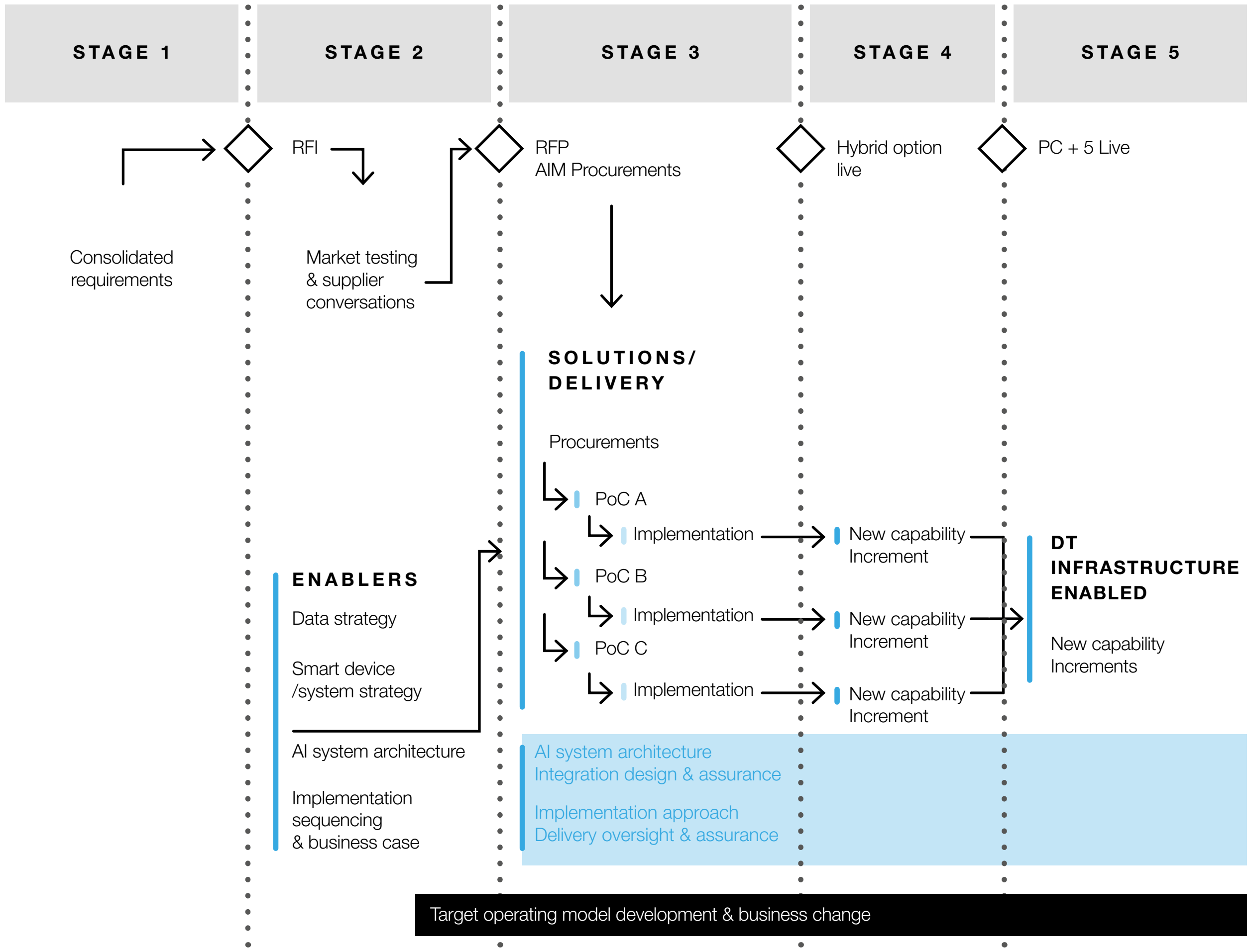


FIGURE 33
Right
An example of various applications feeding into a single digital twin data integrator



outcomes of digital twins at different levels of maturity, as well as the feasibility of each level of maturity. The next steps of the planning process were then mapped out, clearing the way for successful project delivery:

- RFI to understand market capabilities
- Data strategy
- System architecture
- Smart device and IoT selection guidelines
- Implementation strategy.

DEFINING THE SCOPE

We took care to define a high-level design for the campus digital twin at this early stage of the project. This design is built around capability blocks (Figure 34), which schematise the most important user requirements. Armed now with a solid understanding of the problem, and after iterative refinement of the appropriate strategy, we have collaboratively produced a clear roadmap towards the final digital twin infrastructure.

NEXT STEPS

Over and above the ongoing work described in this case study, Arup has been asked to expand the project to consult on further core capacities of the R&D facility such as soft services including catering, cleaning, waste etc. This work will help the client to build a business case for an R&D-wide digital twin infrastructure, which would augment analytics and simulation components of the R&D digital twin with even richer information. ■

FIGURE 34

Opposite left

Roadmap towards the final digital twin infrastructure

MEET THE TEAM

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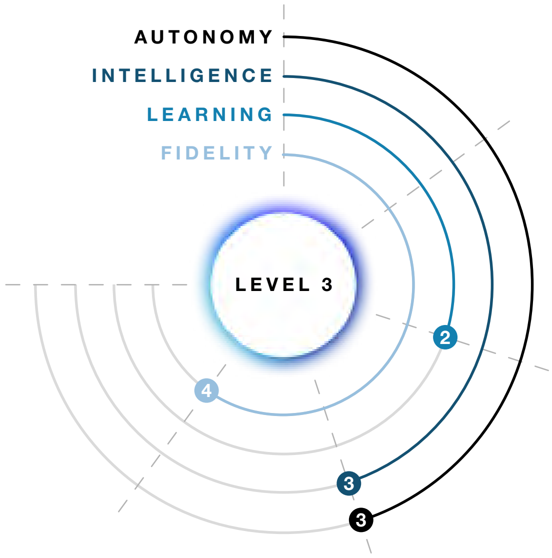
Senior Consultant

BEATRICE NASSI
Senior Consultant

ANDY KERVELL
Associate

CASE STUDY: HONG KONG

Neuron Digital Hub Platform: a data-driven approach to achieve sustainability



BACKGROUND AND MOTIVATION

Modern buildings are complex amalgams of different technologies and systems. Those who run these facilities face many challenges, including getting up-to-date information on building assets, verifying the accuracy of operation and maintenance manuals, checking equipment status, and reliably calculating building performance and energy costs. Although building automation and energy management systems have existed for some time, they tend to focus on monitoring and providing alarm capabilities. But with the increasing convergence of building systems, there is great value to be delivered by a central analytics platform which can provide more insight from integrated data.

Arup's Digital Services team has been researching and developing an integrated 'BIM + IoT + Analytics' platform for smart buildings.[90] The outcome is the Neuron Digital Hub Platform, a cloud-based, centralised management platform which can connect disparate building systems and equipment, making them easily accessible and facilitating their operation and maintenance. The project began investigating the potential of IoT technologies to provide a more comfortable and customisable office workspace. Through subsequent development phases the platform was expanded to include machine learning and artificial intelligence capabilities, before finally maturing into a comprehensive smart building management solution.

The Neuron Digital Hub Platform is an intuitive and fully customisable visualisation tool to engage users, enhance building efficiency and optimise operational workflows. One of the most innovative features of the platform is the interaction between the building's 3D BIM model and real-time data captured automatically from building management systems and HVAC systems. This is achieved using open protocols including Building Automation and Control networks (BACnet) and Modbus. By clicking on an item in the 3D BIM model, operators can visualise specific parameters and statistics for the item with the help of interactive and responsive dashboards, dramatically rendering building performance more transparent.

3D BIM also improves the capability of real-time monitoring of building system parameters. Capturing environmental changes, the integrated platform can generate timely responses to threshold triggers in abnormal situations, reducing energy consumption. The Neuron platform also brings a new dimension to asset management, operations and maintenance ▶

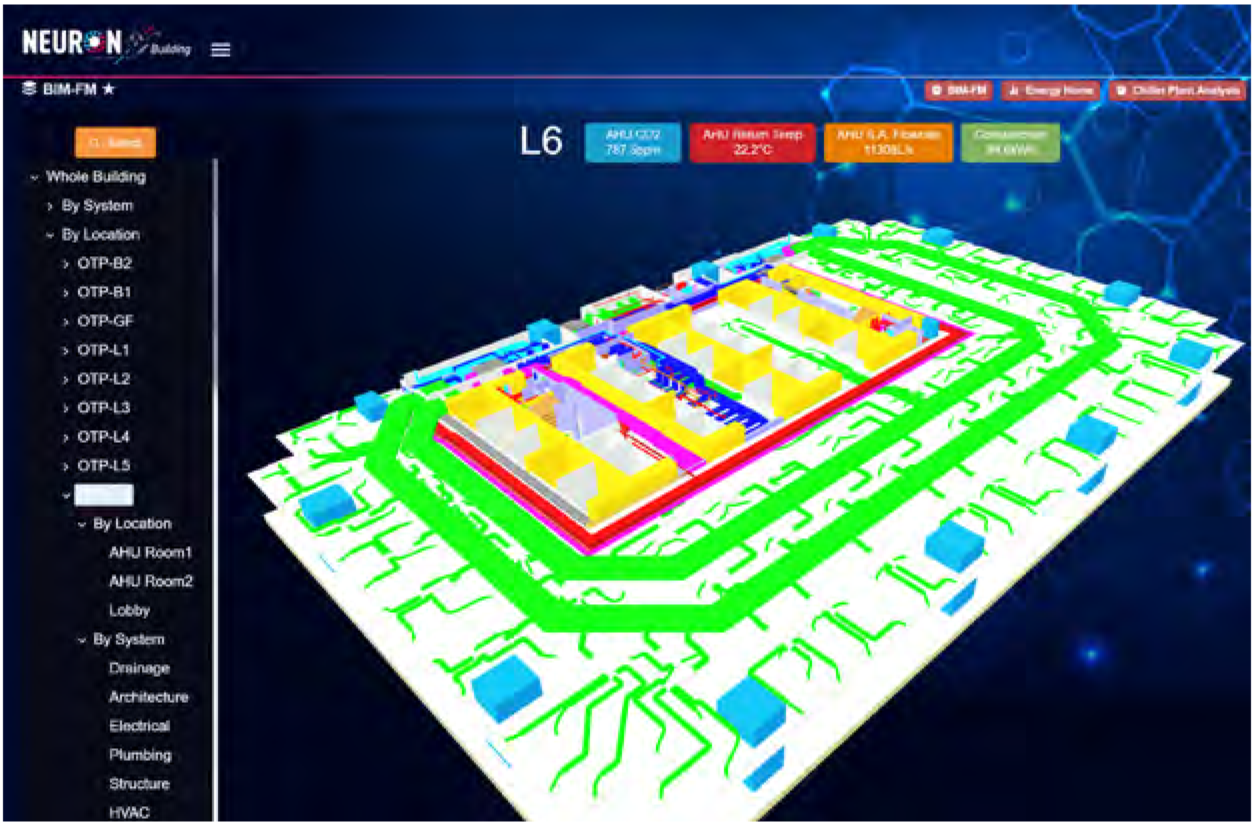


FIGURE 35
Top
A view of the Neuron platform dashboard

FIGURE 36
Bottom
A view of a section of a floor area

by creating a digital twin for each building. With this dynamic real-time view of the integrated systems of the building, operators can quickly retrieve asset information for decision making, diagnose problems remotely and test proposed fixes before having to apply them to physical components.

The Neuron Digital Hub Platform also offers further smart features. Precise measurement of indoor environment parameters such as temperature, humidity, indoor air quality and air contaminant levels are provided by a network of IoT sensors and equipment gateways. By using the computational power of AI together with machine learning, the platform boasts diverse functionality to transform building operations, as follows:

Trend discovery and energy forecasting
Large historical data sets can be analysed to uncover hidden patterns, in order to better estimate future energy usage and allow better planning.

Building system optimisation
The building management system can be controlled and adjusted automatically based on statistical insights retrieved from historical data, leading to automated workflows, energy usage reduction and sustainable building performance.

Fault detection
AI facilitates early detection and timely resolution by identifying anomalies in system data and verifying fault occurrences.

Predictive maintenance
AI helps to monitor and estimate the condition of equipment and its components by analysing usage patterns, frequency of maintenance and operational parameters such as vibration and acoustics. System maintenance can thereby be scheduled, in lieu of disruptive unplanned downtime.

The Neuron Digital Hub Platform has already been applied to several pilot projects, including the iconic Water Cube in Beijing.[91] Through energy usage optimisation and predictive maintenance, substantial energy savings and increased operational efficiency have already been achieved. Additionally, air pollution is a major concern in Beijing, and a network of IoT sensors deployed in the venue continuously monitor the indoor air quality while collecting data to help optimise building system operations.

The techniques and technology embodied by the Neuron Digital Hub Platform represent a culmination of Arup's expertise and innovation in the built environment. The system is constantly learning to improve its own performance, and the data collected will help our clients create better buildings and facilities in the future. The Neuron Digital Hub Platform puts the concept of smart buildings on a new level: it will change the way buildings are designed and constructed, operated and maintained. ■

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Engineer

VINCI FACILITIES

Digital twins for facility management

Vinci Facilities are using the large amounts of data stored in a digital twin to improve maintenance efficiency.[87] On a typical system, a technician may receive an alert which reads “Fan broken, Office 14, Building 3”. What seems like a clear message is actually very ambiguous. What type of fan is it? What parts are required? Where exactly is the fan located? Using the digital twin for the building, a vast amount of information can be accessed by the technician before they reach the job, allowing them to prepare fully for the task in hand. A virtual inspection can be carried out showing the exact type of fan, the most recent maintenance report, a video tutorial and an exact nomenclature. The correct tools can then be prepared to carry out the job. The technician is given an accurate photo of the location as well as the most efficient route to take to reach the job. All of this combined reduces the time spent working out what is required and keeping the actual maintenance time to a minimum.

MARKETS

Transport

The concept of a digital twin is not well-established in the transportation sector, which means that there is an opportunity to take the term and use it to drive progress in a well-defined set of areas.

ISABEL DEDRING
Global Transport Leader
Arup

GERARD CASEY
Senior Consultant
Arup

INTRODUCTION

What can digital twins bring to the transport sector? Perhaps the most promising idea is the 'city digital twin' — a realistic simulation of a city, including the transport network and population. The twin should accurately model changes with the passing of time, given initial conditions, while being reactive to changes and interventions, such as new transport services, new housing developments or changes to fares. Whereas a more familiar kind of digital twin at present might, for example, aid the delivery of a discrete piece of infrastructure, the city digital twin would have the greater scope of delivering broader social and transport outcomes. Furthermore, the city digital twin can be maintained, updated and extended — potentially remaining relevant for as long as the city is inhabited. That new models and new data will change how we operate is undoubtedly true; the question is, what role will digital twins play in this change?

POTENTIAL

A digital twin is a virtual model used to tighten the feedback loop between design and execution. As an industry with modelling at its core, this sounds familiar and reassuring language. But the historic context paints us a picture both challenging and exciting — on the one hand, we in the transportation sector deal with unique, boutique projects every time, which might suggest a preference for single-use modelling. But equally, we see trends and patterns repeating themselves time and again, making the prospect of reusable models highly valuable.

This tension between boutique and more flexible modelling has effectively produced two polarised camps. The latter is typified by tech start-ups who claim to have 'solved' transport modelling for all cities using new data and new models, the latter by those in established quarters who maintain that ▶

we must continue to treat each case study in isolation, using slowly evolving models and fragmented, small data. So, where is the reasonable middle ground? Do we think that years of training data and a black-box machine learning algorithm is a reasonable replacement for a well-understood method with a sample size millions of times smaller? For example, is a machine vision method for tracking cars on a junction better than a traditional (human!) traffic count? Are these even meaningful comparisons? Usually they are not, as they are focussed on somewhat differing questions. In this case the machine vision method will likely give us more than just the traditional vehicle count metric, adding information about how pedestrians, cyclists, cars and other vehicles use this space.

The sector is fairly aware of the limitations of current models and data sources — they are essentially the devil we know, while the Silicon Valley models with slick user interfaces and amazing visualisations tend to fall into the category of the devil we definitely don't know. Transport is a fairly conservative sector for good reason — infrastructure projects require some of the biggest decisions cities and countries ever make. Would we be able to credibly face a public enquiry or local community and justify our building on the basis that “the model said so"? We struggle to do this already, and although our models undoubtedly have flaws, they are significantly more transparent than a neural network trained on a petabyte of sensor data.

CHALLENGES & OPPORTUNITIES

Arguments around the type of model to use are of course somewhat abstract. The more important question is: can digital twins improve project outcomes? Consider large scale station developments — how do we engage local communities in a project with strategic national importance to ensure equitable outcomes for all stakeholders? More broadly, how do we facilitate a shift away from polluting personal vehicles towards public transport? We can schematise some challenges and opportunities found in Table 7.

Our clients task us with challenges like these daily. This explains why Arup is investing heavily in our own internal capabilities, developing state-of-the-art models together with clients, academic institutions and others. These include rapid assessment tools for quantifying the impact of widespread autonomous vehicle deployment in cities, or building multimodal agent-based models of populations with City partners. A dedicated R&D team is currently developing a hybrid model that generates and trains synthetic agents (people) in an entirely digital transport model and compares it against real-world behaviours.

RISKS

The holy grail of transport modelling is to accurately model future scenarios for example, autonomous vehicles, widespread city-centre pedestrianisation, or road pricing. There is a significant barrier to this, however — digital twins have only become viable thanks to new data sources, but these remain heavily biased. Transport for London, for example, began publishing open data on their services ten years ago, while decades-old GPS technology has only seen widespread adoption in the past decade.[92] While useful, this data only captures a relatively short period in our history — even if we had complete access to all of this data, would the training sets be adequate? A digital twin might also struggle to help us with predicting rare or unprecedented events, such as widespread autonomous vehicle deployment. While these negative points will be mitigated over time, as the twin continues to run, these fundamental constraints must be acknowledged.

LOOKING AHEAD

The concept of the digital twin is not well-established in the transportation sector, which means there is an opportunity to commandeer it and use it to drive progress in a well-defined set of areas. These areas must be problem- and outcome-focussed; technology for technology’s sake is always a mistake. Ultimately, there is incredible potential in this domain — the potential to move away from a reactive approach to problems, and towards a proactive exploration of opportunities. ■

CHALLENGE	OPPORTUNITY
Traditional transport models are big, slow and crude. It takes time to build and calibrate models. Scenario testing is often limited by what our models can actually reflect, while running a model can take up to weeks. All this deters interested parties from model deployment.	Moving away from by-project model creation towards a digital twin model adaptable to many scenario testing could democratise transport modelling, reducing delivery risk and increasing stakeholder engagement.
Because of data and computing limitations, we tend to model systems in an isolated fashion, and at incompatible levels of granularity. For example, different means of transport tend to receive different models. A further divide is between operational and strategic models. These models thus rarely interact with one another, reducing their usefulness in scenario testing.	Rather than calibrating our models at discrete time steps (as seldom as once a decade on some major models), we will move towards real-time feedback. As real-world data arrives over time, our models will become more accurate. Since we now have the data and computing capability, our strategic models and operational models can merge, with a strategic model simply being a long-running operational model.
We don't treat people as individuals, but rather as an aggregate. This often entails assuming rational behaviour with perfect access to information, given some behavioural goal. Clearly, this is an idealisation too far.	Individual-level data will sources enable us to capture each unique personality. Unprecedented detail is now available, enabling a behavioural economic approach to users. However, effective ethical and legal protections are required in this domain.

TABLE 7

Top

Challenges and opportunities of digital twins for the transport market

We have had access to increasingly sophisticated modelling of networks like these for years, but the opportunity to connect users of the network (as real-time data streams) to the infrastructure of the network itself (asset performance information) is a sea change.

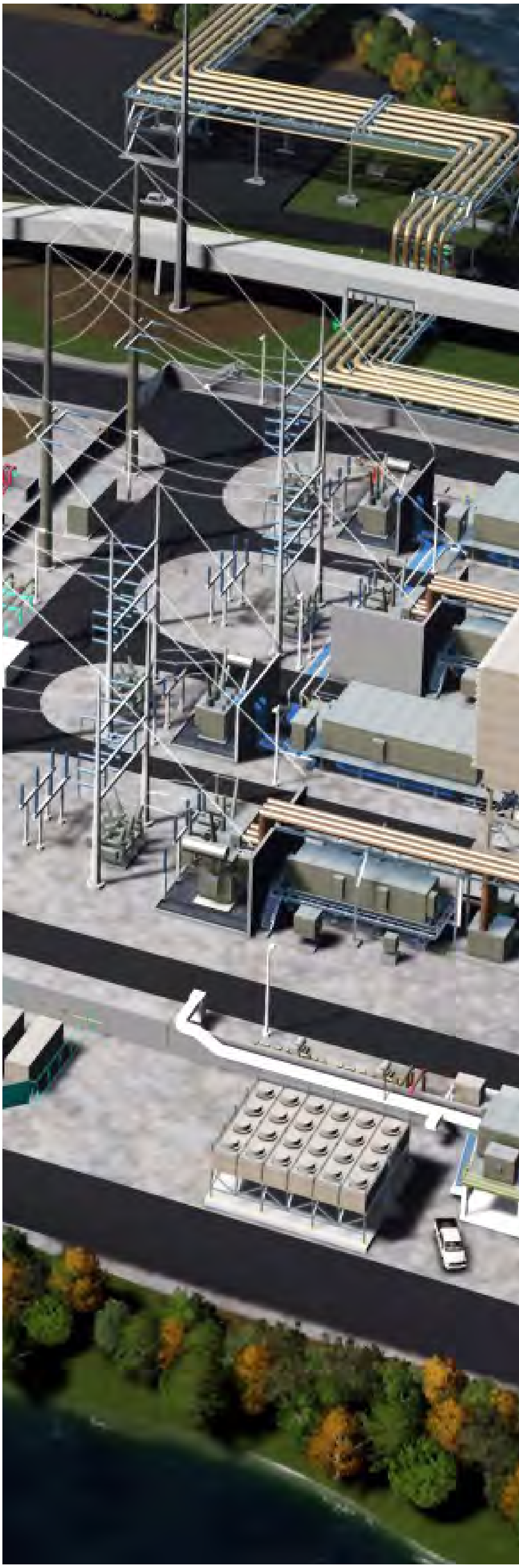


FIGURE 37

Right

Modernisation of Big Bend Power Station in Apollo Beach, Florida, U.S.A. The digital twin was critical to allow visualisation and access to the physical and engineering data throughout design and construction, and will be key to future operation of the facility. Image courtesy of Sargent & Lundy.

DR NABIL ABOU-RAHME
Chief Research Officer
Bentley Systems

Infrastructure networks evolve over time, and, being complex systems, are increasingly interdependent. Managing infrastructure today is about more than just optimising demand in line with available capacity — it's about how that capacity is affected by adjacent systems like weather, ground conditions, and systemic efficiency. It's about how failure in one part has unexpected and unintended consequences in another part, and how we might plan for and mitigate such risk. It's about going beyond the business case for isolated projects and determining, in this age of sustainability, which interventions deliver the greatest downstream benefits.

In the early days of my career, I saw these interdependencies emerging, through the prism of the transport sector. I observed convergences with energy networks on the question of accommodating electric vehicles, with water networks for the challenge of storm water mitigation, and with distribution networks in the context of post-disaster emergency relief.

We no longer need to perform real-world validation, with all its attendant risks, costs, and frustrations. Instead, we can now envisage hundreds of scenarios, leverage machine learning to generate designs, and optimise for multiple parameters.

All this provides the context for digital twins, and why they are essential for infrastructure. Looking at the latest hype-cycle reports from industry, you'd be forgiven for thinking that digital twins suffer from highly over-inflated expectations. But in the ▶

infrastructure sector today, things are turning out differently, in that digital twins are turning out to be a natural point of convergence, rather than an intrusive change. This is clearly no unwanted consumer trend encroaching on our territory. Rather, it's a lifeline which will ensure our viability.

Digital twins enable users to visualise the asset of interest, check its status, perform analysis and generate insights in order to predict and optimise performance. An infrastructure twin incorporates data from many sources to build its repositories — including drawings, specifications, documents, analytical models, photos, reality meshes, IoT feeds, enterprise resource data and enterprise asset management data.

Digital twins span a plethora of use cases across the infrastructure lifecycle. A performance digital twin, for example, may spawn many project digital twins, which are then federated or merged back in. Similarly, a project digital twin may mature into a performance digital twin. A robust understanding of asset breakdown structure will help in determining at what point a system is well-bounded. Each individual digital twin can mature to provide ever-greater insight, through continuous synchronisation, improved digital context, and a detailed chronology of change for the digital twin itself. Not only can they be created rapidly and to a high degree of accuracy from the outset, but they can also be maintained as evergreen in a cost-effective way over the lifetime of the asset. By focusing on the integrated data set rather than the tools used to manipulate the data sets, practitioners become truly data-centric and adept at augmenting the twin with new data sources as they arise.

Bentley Systems participated in creating an area-wide digital twin in the UK, replicating the Institute of Manufacturing building and Cambridge University's West Cambridge campus.

The goal was to demonstrate the usefulness of a digital twin for facilities management as well as to improve productivity and well-being.[93] The visuals were impressive enough, from a flyover of the buildings to going inside and checking detailed sensor measurements spanning back over a year. However, the real innovation lay in the rapid creation of a fully georeferenced and integrated dataset, conforming to the Gemini Principles, which could be read, interrogated, and reproduced by different analytical and visualisation tools.[33] But this is a time for further development, not for satisfaction with what has already been achieved; many more examples will materialise in the coming months.

In predicting the next big breakthrough in digital twin usage, we are faced with an embarrassment of riches.

How will our reality modelling improve, bypassing or validating the sensor reading by taking thermal or visual scans of the asset as part of the synchronisation — guarding the guards, if you will? Human-operated drones are giving way to autonomous swarms and other forms of robotics in research facilities, but will these soon be buzzing around an asset near you? Or, take enhanced images from open satellite data: if our finest technology can see a black hole event horizon when looking into space, then we can surely spot the odd defect in our infrastructure when looking back from space.

When will quantum sensors detecting gravity waves become a cost-effective way of mapping underground infrastructure, and our digital twin ecosystems double in size and usefulness overnight? Why stop at immersive visualisation when we can take semantics and start talking to our digital twins the way we do with chatbots? Or, think of the tokenisation of value over the lifecycle of an asset through smart contracts, oracles and cryptocurrency assets relevant to that model. Will such instant tokenisation mean that early stakeholders, such as designers, are further incentivised by the prospect of skin in the game for years to come, as the real value of their design intention materialises?

To answer these questions and others, Bentley is investing in a collaborative research network with academic and corporate strategic partners, to continue exploring the art of the possible for digital twins. We are excited to share our vision of the future with professionals who dedicate themselves to advancing infrastructure, and thus society itself. ■

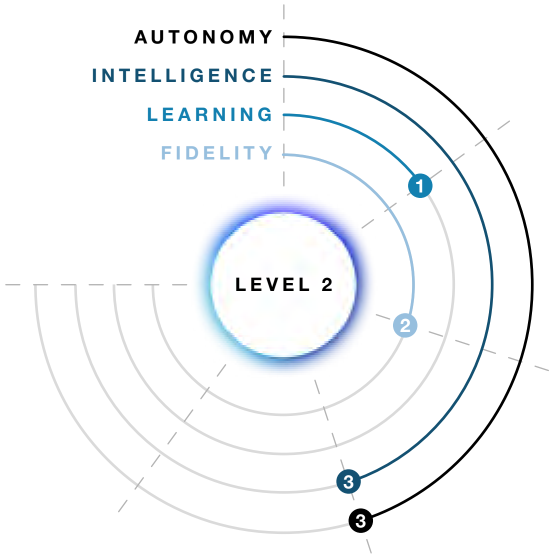
FIGURE 38

Top

The West Cambridge digital twin demonstrates the impact of city-scale digital twins on infrastructure management and productivity

CASE STUDY: MASSMOTION

Digital twins in the transport industry



HOW DO WE AUGMENT DIGITAL TWINS TO UNDERSTAND THE CHANGING IMPACT OF PEOPLE ON TRANSPORTATION FACILITIES?

Tracking and measuring passenger traffic flow can inform design and optimise both performance and customer experience in domains as disparate as public transport and concert hall design. An understanding of the qualitative and quantitative characteristics of crowds in specific spaces aids asset owners to ensure safety, comfort and efficient transit.

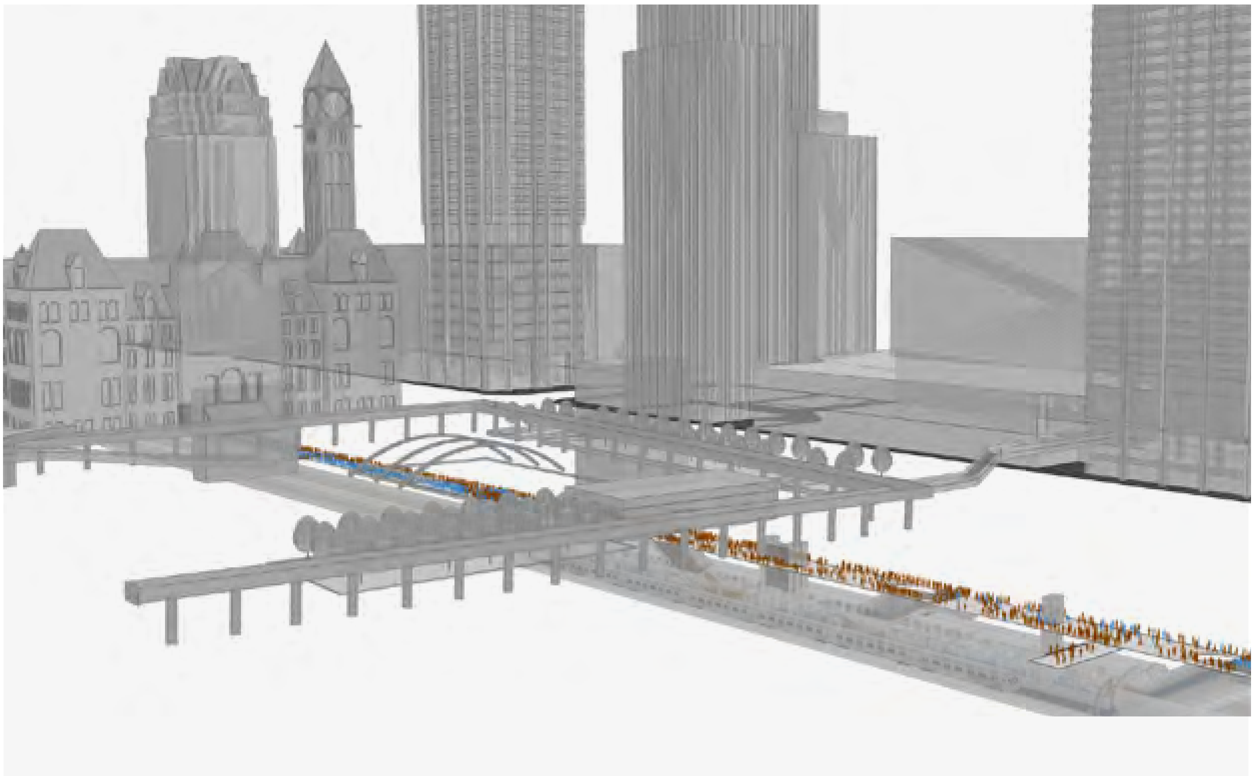
Arup's MassMotion software has continually innovated over recent years to become the industry-leading crowd simulation package we know today.[94] Its BIM-compatible workflows and native 3D environment allow rapid testing, providing feedback on congestion and thereby allowing optimised design.

MassMotion is used for such eclectic building typologies as railway stations, airports, commercial buildings, art galleries, and stadiums, and makes use of various classes of input data to shape designs from a human perspective. This commonly includes a 3D model of the space under consideration, along with information on travellers' origins, destinations, and any intermediate nodes in their journeys.

REAL-TIME CROWD CAPTURE WITH MASSMOTION LIVE

We now inhabit a world where everything from sensor data to sentiment analysis to CCTV footage is channelled wirelessly to provide real-time information on people's movements and motivations. Transport facilities can make good use of this data in operational and long-term planning, but only with appropriate intermediaries. MassMotion has therefore launched an ambitious research programme — MassMotion Live — to incorporate this data into a digital twin workflow.

MassMotion Live will significantly enhance the existing product to enable near-real-time capture and visualisation of observational data, as well as to develop new behavioural models which better simulate pedestrian motion in particular spaces and scenarios. This will crucially involve the capture of live data to produce detailed records on the range of movement types in transport facilities. We typically design these facilities for commuter populations, but the ability to extract data on tourists, off-peak users, and so on will increase realism and thus aid simulation. ▶



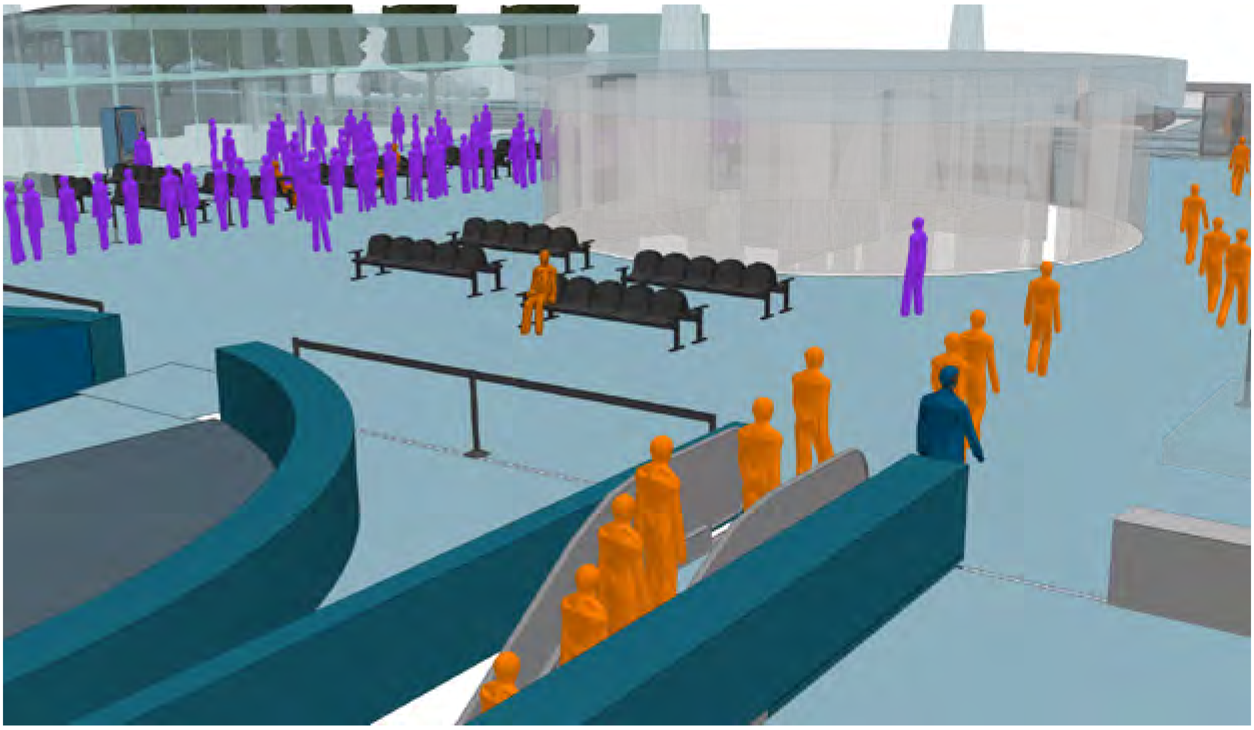


FIGURE 39
Top
A MassMotion model at neighbourhood scale

FIGURE 40
Bottom
MassMotion model of a rail station

DIGITAL TWINS: INCREASING THEIR APPEAL TO THE TRANSPORT INDUSTRY

As well as their eponymous primary function, transportation facilities often serve as hubs for retail, commerce and leisure. As focal points of urban stimuli, these facilities also tend to evolve over time to meet new use cases. They undergo upgrading and expansion, as well as adapting to modern standards in areas such as inclusive design for age or disability. Pedestrian modelling tools already attempt to simulate these ever-changing conditions, but are often fatally hamstrung by incomplete data. This means that currently, they are not particularly attractive to clients — there is thus great scope for improvement and increased uptake.

Most pedestrian models, including MassMotion, are based on a combination of academic research into human movement and validation against industry standards. One example of this is the Fruin standard for density used in facility planning in the transportation sector, where various crowd density levels are ranked and colour-coded based on movement restriction.[95] While this combination generally produces accurate representations of human movement, those representations are commonly based on historical information. However, demographic and behavioural trends are changing rapidly, and designers must be on top of these changes. MassMotion Live gives planners and designers the option to use contemporaneous data as the baseline for modelling, to understand context and user types on a case-by-case basis. In this way, existing generic models become digital twins of specific assets, greatly increasing their appeal to asset owners.

SHORT- AND LONG-TERM BENEFITS

The aim of augmentation of pedestrian models with near-real-time data is not simply to create standalone digital twins. Instead, it is to empower our design tools to provide inputs for federated digital twins, such that all aspects of a facility are captured for optimal testing. The MassMotion team will develop data pipelines to ensure that designers and planners can engage with all available data sources according to project requirements, all while keeping a close eye on the security and regulatory contexts.

Transportation infrastructure is always a major investment for cities, with major recent examples including such as High Speed 2 in the UK, Melbourne Metro in Australia, and Istanbul Metro in Turkey.[96,97,98] Major interchange stations are usually designed with lifespans of 50 to 100 years in mind, based on limited population projections based on limited population projections (e.g. using census data) and with a focus on commuters. Once they are accompanied by their digital twins, however, these facilities can be thought of less as static investments, and more as evolving spaces in line with their actual use.

MASSMOTION: A KEY CATALYST FOR CONFIDENT CITY PLANNING

Current patterns of urbanisation and migration suggest that 80% of the world's population will live in cities by 2050.[99] Ambitious transportation networks will be vital to ensuring that cities operate in an efficient and equitable manner for residents and visitors alike. Similarly, ensuring that these facilities are responsive to changing use patterns, and can quickly adapt to new ways of moving and altered demographics, will be critical in giving cities the confidence to invest in these transformational projects.

Since its inception, MassMotion has been at the forefront of mapping and understanding the impact of human movement on transportation design. By harnessing new sources of data, MassMotion will be a key input to digital twins in transport, not only through its state-of-the-art forecasting of facility usage patterns throughout the design process, but also by linking with other tools in order to contribute to shaping a better world for the end users who live in cities. ■

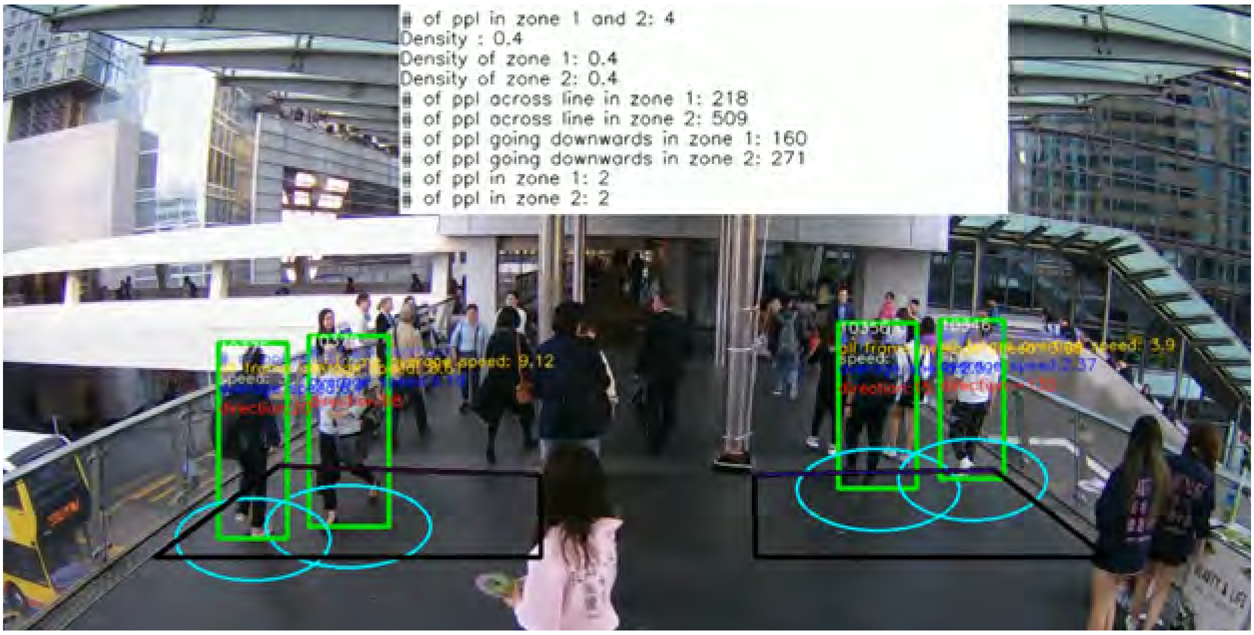
MEET THE TEAM

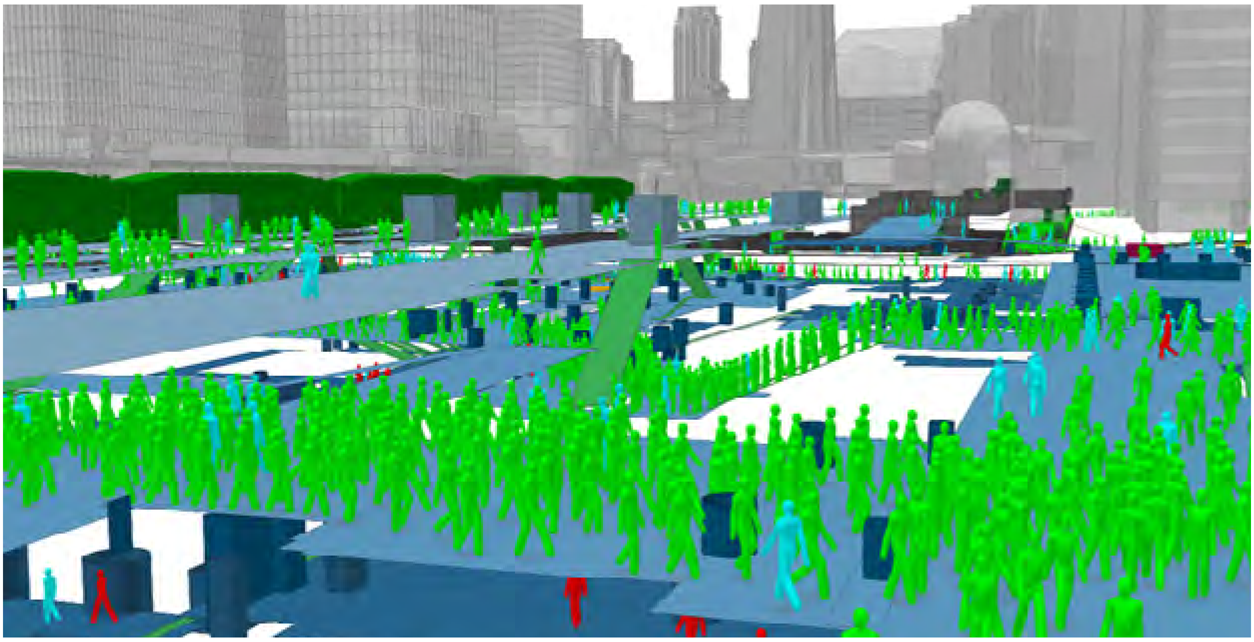
IAN MACKENZIE
Senior Software Developer

EDITH CHOW
Software Developer

LACHLAN MILES
Associate

MICAH ZARNKE
Technical Lead





▲

FIGURE 41

Top

MassMotion modelling of a transportation hub and public realm

▲

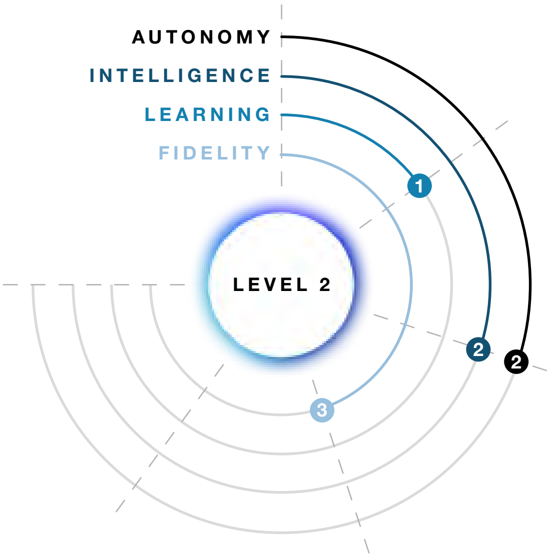
FIGURE 42

Bottom

MassMotion Live research initiative into computer vision people tracking

CASE STUDY: REAL-TIME EMOTIONAL SENSORS

How can we use biometric data to determine user experience?



INTRODUCTION

Arup teams in Hong Kong and Canada are building a digital twin for airport planning and operation, dubbed the Total Experience Lab (TEL): a tool which synthesises three existing modules and one original technology. The TEL draws on various platforms to generate, gather and analyse passenger behavioural data. The platform combines MassMotion, Crowd-sourcing and Mobility Mosaic to create a real-world visual simulation. It then overlays data from the recent Emotional Mapping initiative, using real-time biometric data to map emotional states as users interact with their environment.

The aviation industry has expanded dramatically over the past twenty years, and airport terminals are busier than ever. Passenger numbers rose from 1.4 billion globally in 1998 to 4.6 billion in 2019.[100] Such passenger traffic growth combined with evolving passenger demands obviously has repercussions for the level of service provided by airport facilities. Operators will need to adapt to the growth by expanding capacity, firstly by physically scaling up airport facilities, but also by optimising operations — with the aid of digital twins.

In addition, design and operation considerations now see user experience as a primary factor in successful performance. Understanding how citizens experience their built environment can help us to develop and re-develop a smarter city at every scale. This will allow us to create dynamic and adaptable spaces, buildings, and urban systems which are capable of accommodating the changing behavioural patterns of users. This requires the definition and quantification of a person's experience, considerations often overlooked by modelling systems which measure behavioural patterns such as footfall, while ignoring the complex nature of environmental experience. Current approaches leave us with potentially inaccurate data, which can lead to ineffective solutions.

TEL uses individual experience and the changing behavioural patterns to inform dynamic environments, putting the user at the heart of design. This is particularly important in airports, spaces which often deal with massive passenger flows within very tight operational constraints, creating high-stress environments which can even deter passengers from flying at all. A fuller understanding of passenger experience can help to alleviate pain points, improving facilities and operations for the benefit of users, staff and airlines.

With the Emotional Mapping initiative as its centrepiece, the TEL can elucidate passengers' emotional status and cognitive states throughout their

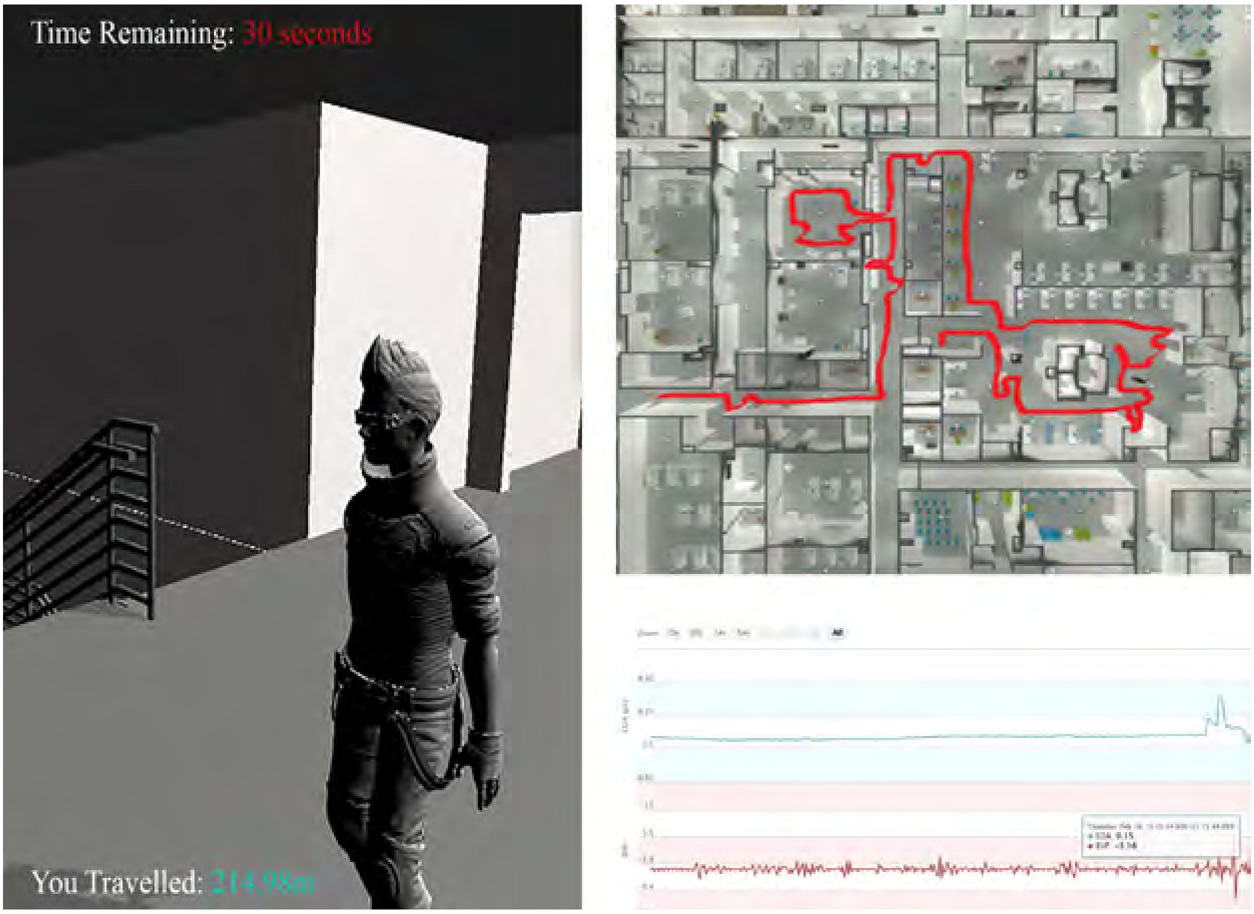


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FIGURE 43

Above

Emotional Mapping: Monitoring biometric data in response to the user experience in the VR environment

journey. Overall, operators can keep user experience at the forefront of their consideration, with near-real time feedback. TEL combines the following four technologies to achieve this:

MASSMOTION

MassMotion is among the most advanced pedestrian simulation software packages. It allows designers, operators and authorities to test design and operation alternatives without limit, using crowd modelling technology. In conjunction with an experiential design component, MassMotion can be used to optimise user experience, for example by management of passenger flow.

CROWD-SOURCING DESIGN FEEDBACK

Crowd-sourcing is a virtual platform which allows designers and operation managers to capture user journeys in the virtual environment. It allows users to explore design options in a game-like environment, and simultaneously to capture users' behavioural data. This application is widely used to optimise design. ▶

MOBILITY MOSAIC

Mobility Mosaic is an app that collects location information and intelligently identifies trips and modes of travel.[101] Combined with insight from Arup's human factor specialists, the app presents an unprecedented opportunity to understand preferences and behaviours. Mobility Mosaic is heavily used by Arup to consolidate real passenger and pedestrian experiences in order to design transport services that meet genuine needs.

EMOTIONAL MAPPING

The ultimate goal of Emotional Mapping is to understand individual users' subjective experiences of spaces. Since passengers' emotional responses constitute their true experience of their environments, the project aims to render a real-time map of passengers' emotional status as they interact with a facility or process.[102] This is achieved by collecting biometric data and conducting post-survey and real-time survey analyses. Data can pertain to cardiovascular or respiratory systems, electrodermal activities, muscular systems and brain activities, as well as analysis of body language or behavioural responses. Information of this type is superior to conventional methods which use self-reported questionnaires, removing the user from the environment and requiring them to take a retrospective evaluative stance, which is necessarily inhibited by perception and experiential variability. By failing to describe the unpredictable and ever-changing nature of human experience, current approaches fall short of providing accurate and reliable data upon with which planners, designers and authorities can make decisions.

The TEL integrates all of the above platforms, creating a human-centric digital twin which provides a real-time replica of passengers and their interaction with their environment. Such a digital twin reflects passengers' real-time experience, as well as generating new scenarios when the environmental context changes, physically or digitally. With this data, human-factor analysts can address problems as they are identified, running them through the TEL to evaluate alterations from a user experience perspective.

The fusion of the operational digital twin and the human-centric digital twin enables all stakeholders to understand the impact of any operational change to passenger experience. The focus is not only on optimising operation, but also on offering a dynamic multiple-criteria decision analysis to all stakeholders, in order to reveal the impact of any decision.[103]

This digital twin will allow designers and operation managers to discover previously unexplored solutions without risk to operations or passenger experience. We want airport authorities to have access to the best possible real-time data, putting them in a position to face the ever-evolving nature of passenger needs. Further, new technologies will in future make it possible to analyse the overall performance of an airport terminal.

VR technology, with its ability to simulate complex situations, also offers researchers an unprecedented opportunity to investigate human behaviour while trialling various structures and systems. This will dramatically increase the likelihood of optimal results from the final built structures.

Finally, the project will also contribute to the rise of 'smart citizens', connected interactively to responsive environments. The greatest challenge in all of this is that people experience emotions differently, based on factors including but not limited to culture, age, gender and metabolism. EM must be honed to accurately identify emotional experiences in the face of individual variation. ■

MEET THE TEAM

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Associate Director

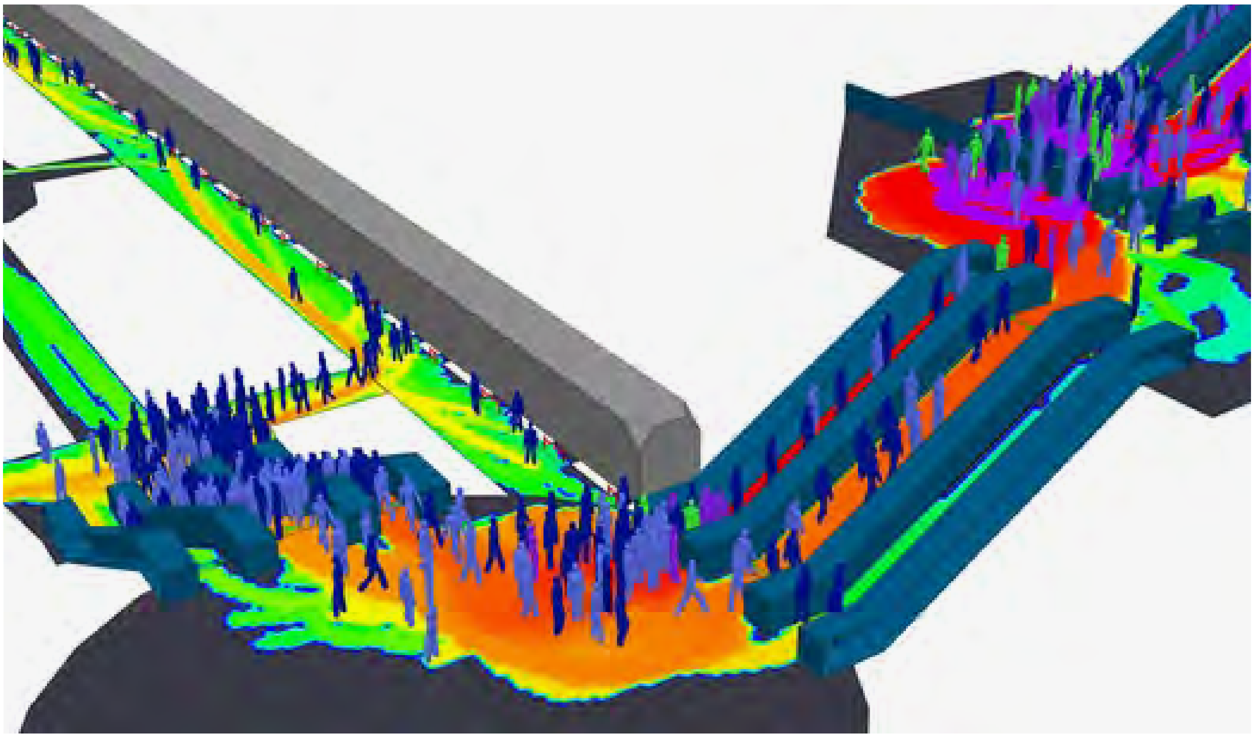


FIGURE 44

Top

MassMotion's pedestrian simulation and crowd analysis tools for a transit station

FIGURE 45

Bottom

Crowd-sourcing design feedback: a user view of the interactive 3D environment

Determining the health of ships

DNV GL has developed a methodology for hull condition monitoring incorporating the ship's digital twin, a virtual model prepared during the design stage.[104] As part of the Nerves of Steel Extraordinary Innovation Project, DNV GL — Maritime has been investigating ways of calculating wave damage to ship hulls. Significant amounts of time and money are spent by ship designers and shipyards in preparing analytical models to document the design of ships and offshore structures and to perform simulations.

The use of this virtual model as a digital twin during operation of an asset would allow the visualisation of key components and improve the understanding and control of the long-term effects of operation on the ship's structural and functional components. Such a digital twin could aid inspection and maintenance planning, extending the lifetime of the ship through prevention to hull damage.

WILLOW & TRANSPORT FOR NSW

Creating a data-centric network

Transport for New South Wales (TfNSW) is implementing Digital Engineering (DE) to connect emerging technologies with reliable structured data. Willow is helping them to resolve variations between current standards, provide gap analysis, specialist advice and implementation on global best practice for DE standards and advise on implementation.[105] While success with DE has been realised within industry, implementation is more complicated when applied to an intricate multi-modal transport network. By building their assets twice — first virtually then physically, TfNSW can create 3D models to connect a massive amount of data in the planning, detailed design and construction stages of projects — improving coordination and oversight during construction and efficiency during the operation and maintenance of their assets.

DE brings together systems and related data sets into a common data environment, connecting the static data of asset information & documentation with live data of IoT devices, control and visualising systems them in a geospatial context (such as GIS mapping or 3D models in BIM).

KONECRANES

New standard for the Crane Industry

Konecranes, a Finnish company who manufacture and service cranes and lifting equipment, has implemented the Siemens digital innovation platform, including MindSphere, an open, cloud-based IoT operating system, and the Teamcenter® portfolio, the widely used digital lifecycle management software, to leverage the digital twin.[106]

Design, simulation and prototype testing organisations often operate in their own silos, using out-of-date processes. At Konecranes, a digital twin was utilised to review data and provide feedback around engineering, simulation and testing intent. Using the Siemens platform, Konecranes has connected the data to create a 360-degree view of how prototypes are running and performing, correlating requirements to real-world performance data. A closed-loop digital twin framework, using IoT and PLM technologies, can lead to quicker resolution of design issues. Leveraging virtual sensor data in product simulations to provide accurate results can lead to improved overall quality, shorter prototyping phases and support downstream for product lifecycle processes.

The Konecranes proof of value is one of the first implementations of IoT to develop a framework that connects and synchronises the virtual (engineering design, analysis and simulation) and physical (testing and operational reliability) worlds.

WILLOW & STRUKTON MOBILITIES

New level of smart rail maintenance

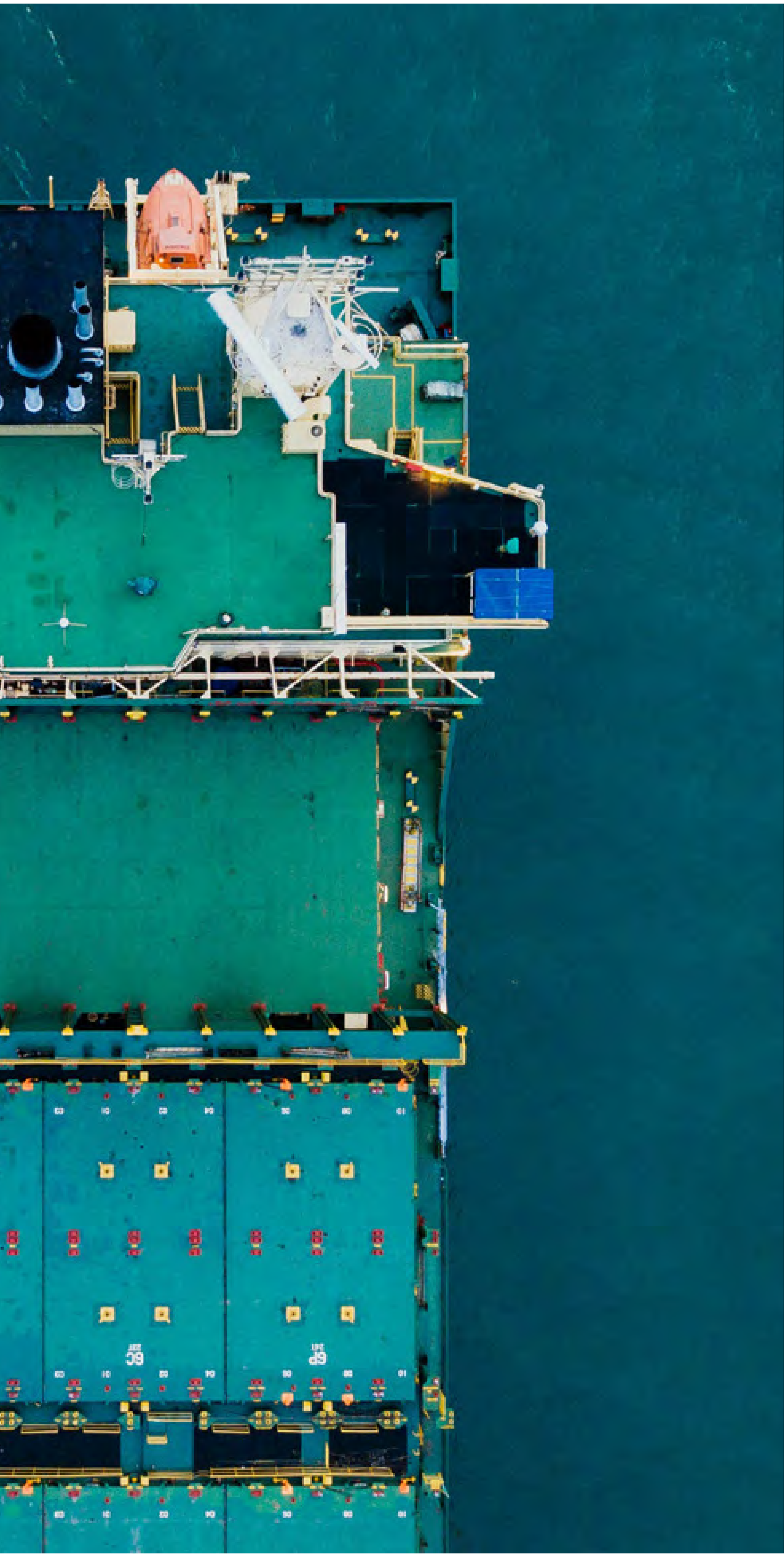
Willow and Strukton have come together to change the way we view and manage rail systems.[107] In the heavy haul sector, disruptions and delays caused by the condition of the network can result in hundreds of millions of dollars in damage. Up until now the vast amounts of data that are required to maintain and run a railway are held up by individual silos, inaccessible to the asset managers who are having to make decisions without the full picture of information at their disposal, and on critical decisions are having to join the dots themselves. A complete digital twin of the entire rail network can be viewed in real-time, giving the asset manager a holistic view of the system. Combining all the previously disconnected information in one place allows the data to be turned into valuable insight. Predictive maintenance and network capacity improvements are just some of the far-reaching impacts.

APOLLO 13

NASA's Original Digital Twin

Michael Grieves is commonly said to have coined the term 'digital twin' in 2003.[1] However, the concept had become reality long before the modern terminology. This realisation dates to the 1960s; specifically to NASA's Apollo 13 spacecraft.[108] The craft was designed and planned using simulations. The models became vital in rescuing the three-man crew, over 200,000 miles from Earth, following the potentially disastrous explosion of an oxygen tank in the craft's service module.

The digital twin on Earth was used to model solutions. NASA's aim was to operate, maintain and repair physical systems while they were in space. The success of the mirrored system during the Apollo 13 mission led the agency to develop more advanced digital twins for all subsequent missions.



ROLLS ROYCE & SVITZER

Operating full fleets of autonomous vessels

Rolls-Royce and Svitzer - the global towage operator - have successfully demonstrated the first remotely operated commercial vessel in Copenhagen Harbour in Denmark. Manoeuvres by one of Svitzer´s tugs, the 28 metre long Svitzer Hermod, were controlled remotely by the captain of the vessel who was stationed at the remote base at Svitzer headquarters.[109] The vessel was berthed alongside the quay side in Copenhagen Harbour, undocked, turned 360°, and piloted it to the Svitzer HQ, before docking again. The Svitzer Hermod is equipped with a Rolls-Royce Dynamic Positioning System, the key link to the remote-controlled system. Using advanced software, a range of on-board sensors combine different kinds of data which is transmitted to a Remote Operating Centre (ROC) from where the captain controls the vessel. Input from experienced captains went into the ROC design to place the different system components in the optimum position to give the master confidence and control. The aim is to create a future proof standard for the remote control of vessels.

OCADO SMART PLATFORM

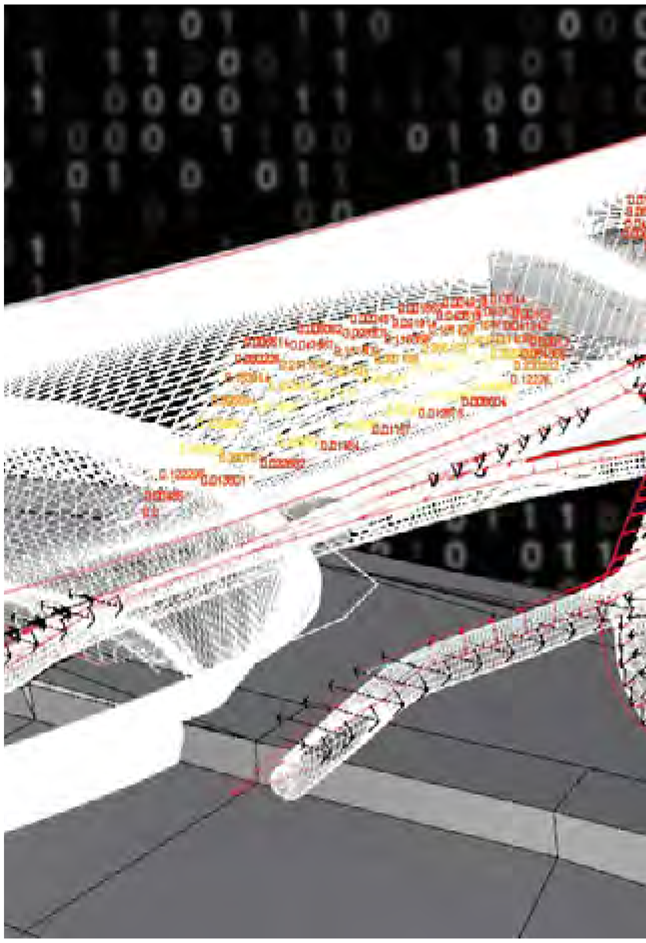
Automated storage

Ocado fulfils over 300,000 orders a week and delivers these with 99.8% order accuracy. In its highly automated warehouses, the most sophisticated of their kind in the world, thousands of bots collaborate like a swarm on a giant grid called 'The Hive' to pick an average 50-item customer order in under 5 minutes. Ocado builds high-fidelity digital twins of its warehouses and other parts of its business to de-risk the physical world and uncover paradigms that might otherwise remain out of sight. These digital twins enable Ocado to evaluate new algorithms, test production software before it is deployed, optimise systems, and even generate data to train ML models before the real data exists. Ocado is also working on plans for "living labs" where they, and other organisations, experiment before autonomous vehicles and related technologies are widely adopted on the public roads and in smart cities. This will enable testing of the provision of smart services in real-life scenarios such as offices, hospitals, shops, schools, universities, and residential properties. These 'living labs' will provide digital spaces for organisations to get their feet properly wet before the Industry 4.0 tide rolls in.

MX3D & AUTODESK & ALAN TURING INSTITUTE & ARUP

3D-printed smart bridge

An expansive collaboration of partners, encompassing mathematicians, structural engineers, IoT specialists and computer scientists, has come together in the Netherlands to produce a true original. MX3D, with help from Autodesk, the Alan Turing Institute and the Amsterdam Institute for Advanced Metropolitan Solutions, produced both a prototype and final version of the world's first 3D-printed bridge, spanning twelve metres and printed with stainless steel.[111] The bridge was designed and installed with a fully functioning digital twin, delivered by the Alan Turing Institute and supported by Autodesk's cloud services, which support the bridge in collecting and processing data. AMS will then apply the data, which concerns structural factors such as strain, displacement and vibration under load from pedestrians, cyclists and motor vehicles. Simultaneously, environmental factors such as air quality and temperature are measured. These measurements inform maintenance scheduling, as well comparison of the performance of real and digital structures. This will allow designers to create better 3D printed structures in future, informed by the data collected. The bridge will span one of central Amsterdam's many canals, the Oudezijds Achterburgwal.[112]



Skywise digital platform at Airbus

As part of its digital transformation initiative, Airbus and their partners have developed Skywise — a platform built to make available all the company's data in one place.[113] It is accessible to employees and suppliers, and has several levels, ranging from servers, to data management applications, to applications tailored to specific processes. At the core of the programme is its ability to extract and link information from heterogeneous sources, which were not originally intended to be compatible. Airbus were able to demonstrate this to be possible within three days. Next they created a system to discriminate data types according to importance, accounting for confidentiality levels. The system has yielded a 30% reduction in ground time for aircraft at airports which are not their usual bases of operation.

Skywise has swiftly provided the company with a deeper understanding of factors such as part durability; it has made maintenance scheduling more efficient; it has allowed the company to anticipate supply chain complications, and may even be able to inform optimal cockpit design. Of particular note is the decision by Airbus to make Skywise open to its many suppliers, an openness that is paying off.

MARKETS

Water

The digital revolution is transforming the water sector and technological developments are opening new possibilities, but it is an integrated approach that will secure the future of water.

RICHARD BOWDEN
Digital Software, Insight and Operations Leader
Arup

INTRODUCTION

Our most precious resource is at significant risk and we must act now. At Arup, we have been developing our 'Design with Water' framework, which draws on our experiences of designing, implementing and maintaining water infrastructure around the world.[114] Design with Water is strongly underpinned by our research activities.

The framework places an understanding of the local water cycle at the centre of responses to wider local issues, such as economic development, food and agriculture, community, and energy use. In order to account for the whole water cycle, Arup conducts research into multiple aspects of water management. From flood modelling assisted by machine learning, to working with partners to better understand water resilience in cities, we are continuously broadening the expertise that enables us to assess risks and support our clients in taking a strategic approach to water usage and management.

Underlying all of our work in water is the goal for the knowledge that we generate to both enable and accelerate the realisation of the water related UNSDGs.[115] The digital twin approach will be an important element in building this knowledge.

THE CHALLENGES IN THE WATER BUSINESS

There are multiple global challenges around the provision, quality and accessibility of water, as well as the impact of human activity on this precious resource. In most cases, these challenges are a mixture of digital, physical and biological factors, but also social issues, driven by the advance of the Fourth Industrial Revolution.[116] ▶

A strict, discipline-driven classification is no longer possible and an isolated approach to developing solutions is to be discouraged. To ensure a sustainable future for water, we need multidisciplinary teams with broad expertise, and we must engage a range of stakeholders.

WATER FOR CITIES AND COMMUNITIES

Growing demand for water in expanding cities calls for insights on the upgrade and future-proofing of existing assets, and on building new state-of-the-art assets with an extended lifespan and which support more sustainable water use patterns. Cities and communities must also learn flexible water-use strategies, to enable themselves to stay afloat both when there is too much water, and when supplies are limited.

ENABLING FLOW IN VIRTUOUS CIRCLES

Water carries both valuable compounds and pollutants, often at the same time. Closing resource loops will help recover value and prevent pollution from spreading. We need to understand how we can best implement the circular economy approach, which technologies are required, and where the opportunities for cross-sector collaboration exist that will amplify the potential benefits.

CAPITAL, GOVERNANCE AND FINANCE

The rise of megacities and the increasing power of local authorities is influencing decision processes, ownership models and investment capacity. A knowledge of novel financing and funding mechanisms, methods for capturing the value of social and natural capital, as well as approaches to community engagement are some of the crucial issues to be explored in the support of sustainable development.

TECHNOLOGIES TO ADDRESS MAJOR CHALLENGES

Emerging pollutants, oceans full of plastics and microplastics, anti-microbial resistance being transferred through water: these are just some of the challenges that require novel technological solutions. Many of them will need to be applied in different industries, and as such, cross-disciplinary collaboration will be vital.

WORKING WITH AND FOR NATURE

We need to ensure that the impacts of our activities on the environment can be minimised or even reversed. Design and development should be nature-aligned, nurturing biodiversity and ecosystems, and simultaneously enhancing our health and wellbeing. Looking for innovative solutions and technologies, while taking inspiration from nature, can help us to develop more effective — but not necessarily more complex — solutions.

DIGITAL INNOVATION SHAPING THE WATER INDUSTRY

We need to continue investigating how digital innovation can support management in each of the water cycle phases. The potential impacts will be significant, and there are still many applications yet to be discovered. Digital technologies can have associated risks; and digital twin technology can provide important information on how best to mitigate these risks.

DIGITAL TWIN IN WATER

Working from the definition of digital twin in the introduction to this report and applying it to the Water business sector, we need to be mindful of how modelling approaches have been used previously.

The water sector has achieved a high level of fluency in digital modelling application as illustrated by:

- Hydraulic models, some extremely detailed and sophisticated, support planning decisions, problem solving, what-if analysis, forecasting and even regulatory reporting
- System-level models, representing bulk water grids, major floodplains or water resource basins, are used to vet operational or development decisions
- Monte Carlo analysis applied in hydrological assessments take advantage of now readily accessible massive computing power[117]
- Smart networks are coupled with machine learning to identify risks, predict failures and estimate future performance.

With this firmly demonstrated success with Water Authorities, the question is not where to go next, or even how far, but only how soon can we get there ▶

with assistance from digital twins? The ultimate outcome would be a city-scale or regional-scale digital twin which combine all the above elements into a powerful tool for decision making by people at all levels of society; government, service providers, communities, businesses and individuals. This can be achieved by:

- Extending and connecting system models to represent the interdependent effects in the real world, such as the impact of a proposed intervention or development on water regimes, urban heat, ecosystem health, carbon footprint, population movements and the economy,
- Using sophisticated hydraulic models as the engine behind visualisation technology such as augmented reality, virtual reality or 3D interactive displays as part of a communication strategy,
- Making water information more personal, and personally accessible, for smart consumers to participate in water and wastewater network transactions and operations.

With the appropriate planning, digital twins could provide a platform for building social equity through combining open access to system information with crowdsourcing platforms to fund improvements that increase equity. The digital twin can provide the replica(s) demonstrating the societal benefits from the funding investment.

CROSS-DISCIPLINARY OPPORTUNITIES

Digital twin enables cross-disciplinary opportunities within the water sector. Within the water sector, water authorities not only provide water for public consumption, but also can provide services related to water quality and pollution, water conservation and fisheries management. In delivering these services, energy is consumed by an authority and the related operating costs and environmental impact is under increasing focus in their efforts to improve efficiency. The digital twin provides a capability to analyse the energy usage under different scenarios by replicating the assets and their energy profile that are managed by the authority.

Related to water, roads authorities are responsible for the maintenance and construction of roads and motorways. From both construction and maintenance perspectives, the management of surface water runoffs and flooding is important for the resilience and availability of the roads to the public. The digital twin can provide a means to simulate and plan for different rain and water flow patterns on a real-time basis and for longer term water planning. ■

The water sector is relatively mature in the digital space, with most entities using technology in digitally fluent ways.

FIGURE 46
Right
Pool visualisation for prospective freshwater pool in Hudson Bay, New York

ELAINE PANG
Australasia Water Skills Leader
Arup

A wealth of asset and performance information is commonly shared among multiple users; sophisticated models are used to understand and predict system behaviour, and interlinked databases and models make possible all permutations of analysis and interpretation. Software platforms are GIS-based, with real world foundations for creating insight. Continuing technological advances mean that massive computing power is now readily available to support advanced assessment techniques, whether using parallelised desktop machines, supercomputers or cloud-based computing.

When considering what is to come in this space, we can first look at what has already been created: models exist which represent the movement of water through pipes, in channels, overland, and beneath the earth's surface. They may be detailed models based on surveyed or as-built asset information, or they may be conceptual models representing large-scale movements of water, as in regional water grids. Verification and calibration of models can be based on disparate sources of information such as pump operating cycles, rainfall radar imagery, river levels and so on.

The models are used to support planning decisions, solve performance and capacity problems, and undertake what-if analyses. Multiple what-if scenarios can be assessed in a relatively rapid manner to vet important decisions on selecting the most robust solutions for an uncertain future. Some pilot projects have combined hydraulic models with gaming concepts to test impacts on user behaviour, while elsewhere, gamification has been tested for system level decision making.

When combined with machine learning and sensor data, the calibrated models support predictive analytics to detect performance trends which signal asset failure, as well as forecasting of future performance. In some instances, the models, once calibrated to real world data, become regulatory instruments for reporting information such as sewage overflows, as a proxy for in situ monitoring.

Comparing the water sector's current technologies with the received definition of a digital twin ►

— a digital replica of actual assets, processes, people, places and systems — we can see that the water sector is already there. Building upon current practices, and considering global trends, some possible directions are proposed for the reader's consideration:

INTERCONNECTED, AGNOSTIC MODELS

Water influences life in so many ways. It makes sense to collaborate across industries to create a city-scale, precinct-scale or regional-scale model which represents the dynamic influences of one sort of change on other aspects of the modelled area. For example, a proposed change of land use from industrial to open space could be analysed in terms of effects on flood resilience, urban heat, population movements, ecosystem health and the economy through a series of linked models (a system of systems), accessible from a central interface.

SOCIALLY SMART DATA SHARING

Today's consumers are sophisticated and expect more access to information. The water sector could adopt the open data concept, adding value by personalising the experiences of each individual. Such a win-win situation would enable consumers to make smarter choices with more control, while water businesses would gain improved insight into user demographics and more direct conversations on the issues that matter, such as water usage, willingness to pay and environmental issues.

The open data concept supports extension into many areas such as building social equity. Combining open access to system information with crowdsourcing platforms could be used to fund improvements that increase equity, leveraging willingness to pay. Crowd sourcing provides a mechanism to take the decision straight to the users; surveys have found that the public is willing to pay for environmentally beneficial actions not normally supported through government funding, such as for cleaner waterways. Open data and crowd sourcing would short cut the political process requiring the election of sympathetic politician to enact laws and policies which lead to funding of the desired outcomes. Present-day decision makers are predicting or assuming what the community is willing to fund, but some projects have been funded initially for feasibility studies and ultimately for the capital cost of construction through crowdsourcing.

NEXT-GENERATION COMMUNICATION STRATEGIES

Visionary projects need visionary communication tools. Sophisticated hydraulic models could drive visualisation technologies such as augmented reality, virtual reality or 3D interactive displays as part of a communication strategy for topics such as proposed capital works, community education, or anticipated changes. Typically, what may appear to be a new paradigm is built on the strength of that method being demonstrated elsewhere, requiring an initial leap of faith from the first adopter. Visualisation, coupled with digital twin technology, can provide the required confidence for decision making and agenda setting.

These advances in digital water can be speeded by the further development of existing concepts such as:

Stakeholder collaboration
Acknowledgement of the potential shared value, and standardised means of articulating that shared value, would support better collaboration among stakeholders and thus the usefulness of interconnected digital twin models. Work has already been done to monetise benefits, such as resilience impacts, blue green infrastructure outcomes and increasing service measures.

Open data
Further collaboration is needed on aspects such as data standards, privacy issues, data warehousing logistics and information security methods for making and recording secure and transparent transactions.

Model interconnection
It should be possible for models to be linked into a system of systems using heterogenous modelling software, combining the strengths of each. Standard IT architectural practices such as ReST (Representational State Transfer) were created for this scenario and are widely used today.

Visualisation
Current techniques, originally drawn from computer games such as third person shooters, may be complemented by alternative techniques, which can be sourced from graphic design approaches used in modern marketing strategies. These include more appealing graphics for information design such as hand-drawn or painted media, use of typography to enhance or emphasise information and linking multiple layers of meaning through multiple layers of visuals. ■

FIGURE 47
Above
NSW digital twin

FIGURE 49
Right
Another +Pool visualisation prospective in New York

FIGURE 48
Below
NSW Digital twin

Australia has a unique set of challenges: water-poor and a hot and dry climate.

MIKE WASSELL
Head of Operational Technology
Sydney Water

Being water-poor with a hot and dry climate, Australia faces a unique set of challenges. Sydney Water is the largest water utility by population in Australia, supplying over five million people. We have a long-term vision to be able to run our entire integrated water services from a digital twin platform. With digital twins, we will be able to plan our assets more efficiently; which is particularly important given Sydney's population is growing at 2% per annum. If we can avoid building an extra 10% worth of assets because we can save 10% worth of water, that is very significant for us.

At Sydney Water, we have a tradition of incorporating all things data, automation, and increasingly IoT. IoT includes a range of projects which are helping to improve our customer experience and enable more targeted decision making. One of the areas we are actively exploring is building digital twins, with a proof of concept developed for one of our largest network assets.

For us, a digital twin is a dynamic virtual representation of a unique physical object, process or system across its lifecycle. It's not just a static digital representation.

Digital twins can provide us with real-time insights into what is going on in our systems. Traditionally, many water companies build hydraulic models based on theoretical principles. Testing hydraulic models using sensors on real-world assets, indicates there can be anything between 10% to 35% inaccuracy. With a digital twin, we have an opportunity to ▶

significantly improve the accuracy of our models. Using real-time data from sensors, we can enable predictive analytics and visualisation to make more targeted decisions about our assets, improving our ability to integrate services across our network. To do this we are looking at a range of applications.

A VIRTUAL PROOF OF CONCEPT

Our proof of concept virtualised a large water pumping station – one of the largest in the southern hemisphere. We used 3D cameras to capture the physical infrastructure, and then mapped asset and supervisory control and data acquisition (SCADA) data to that scan. This gave us a 3D representation which we can use for design and for real-time visualisation of our operations. Our next step will be to incorporate predictive maintenance.

TEACHING SENSORS WITH DIGITAL METERS

Another application is determining the optimal combination of sensors we should install in a network to enable accurate prediction. Part of the way we approach this is to start with far too many sensors, before whittling down to understand the right balance of digital and analogue sensors.

We recently carried out a trial with 10,000 properties in Liverpool, New South Wales to look at the number of sensors required to predict overflows. We discovered to prevent overflows reliably, we require traditional float sensors in every second or third maintenance hole to detect sewer blockages.

Conservatively, we can install analogue sensors in far less locations to achieve the same outcome. The idea is for the digital float sensors, to teach the analogue sensor how to predict an event. In the past, we've looked after our trunk networks using SCADA technology, and our customers were essentially our 'sensors' in the distribution networks – notifying us when things went wrong.

With digital twins there is a real opportunity to change this – to proactively manage an overflow before it happens. Predictive capabilities – if reliable – will have a huge impact on how we can proactively manage our network.

PREVENTING WATER LEAKAGE

Water leaks are another big problem for us where digital twins can help. Water networks leak for many reasons – stress, age, drought and shifting soil conditions.

> We estimate that 20% of all properties have a leak, which means a great deal of water is unnecessarily lost. This is where digital meters (smart meters) can provide much clearer data.

Where we install digital meters, we can measure supply every 30 minutes and quickly inform customers who have leaks. We save water, and our customers save money. Digital meters are not mandatory, but with an uptake of just 10%, our insight into reducing water leakage would be vastly improved. Currently we do not know much about individual usage patterns - how much water is used externally (e.g. watering gardens)? How much is used on washing machines? How much is used for showers? – insights into these usage patterns could help us to be much more effective in how we manage supply and demand.

With digital twins, the biggest value for Sydney Water will be for our long-term planning and asset management. By using empirical system data to guide our design and investment decisions, we will ideally be able to reduce the overall cost of ownership as the insights are fed back into city planning. There are also shorter-term benefits for design, most obviously the ability to preview designs in 3D, to immediately identify construction problems. This will be invaluable in both greenfield and brownfield areas as our city grows.

COLLABORATION WILL BE THE KEY

Our long-term vision is to be able to run our entire integrated water services from a digital twin platform. By exploring applications to improve our real-time insights, visualise a virtual reality of our services and support our customers to make decisions around their water usage, we can set Greater Sydney up for a resilient, water sensitive future.

We've already started installing sensors and are talking to the market about the appropriate platform to build digital twins from single assets to capturing whole integrated systems.

Collaboration between utilities and customers will be incredibly important to get the most out of the capabilities of digital twins. We are currently working with the NSW Government to put in place data sharing agreements across utilities, as well as discussing privacy, security and the challenges these bring.

We are moving into a new digital era and are excited for the opportunities it will bring for our city. ■

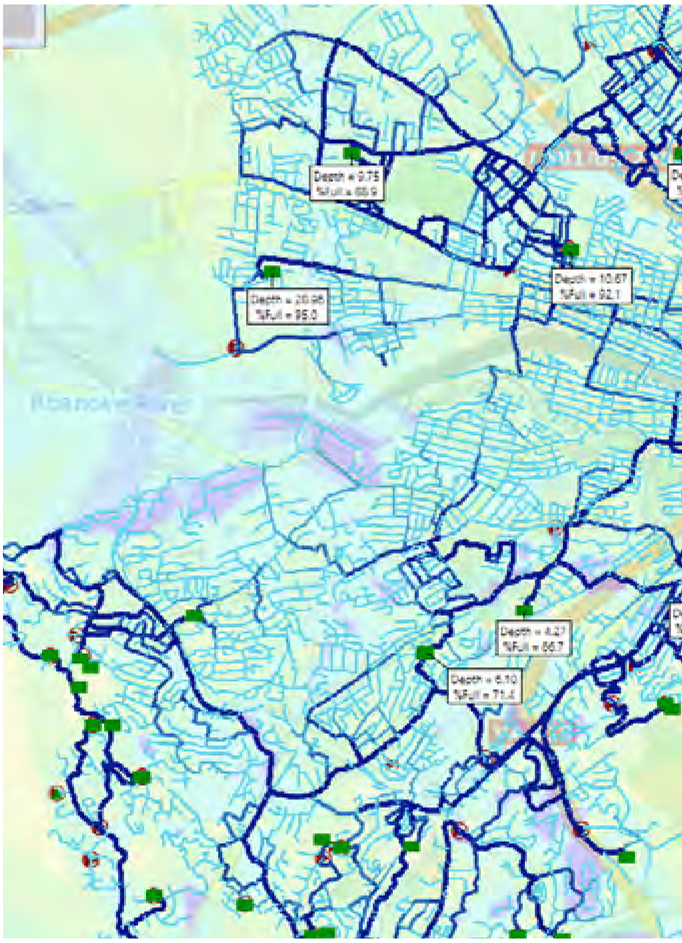
NEWCASTLE & NORTHHUMBRIAN WATER

UK's Water Digital Twin to Help City Plan for Disasters

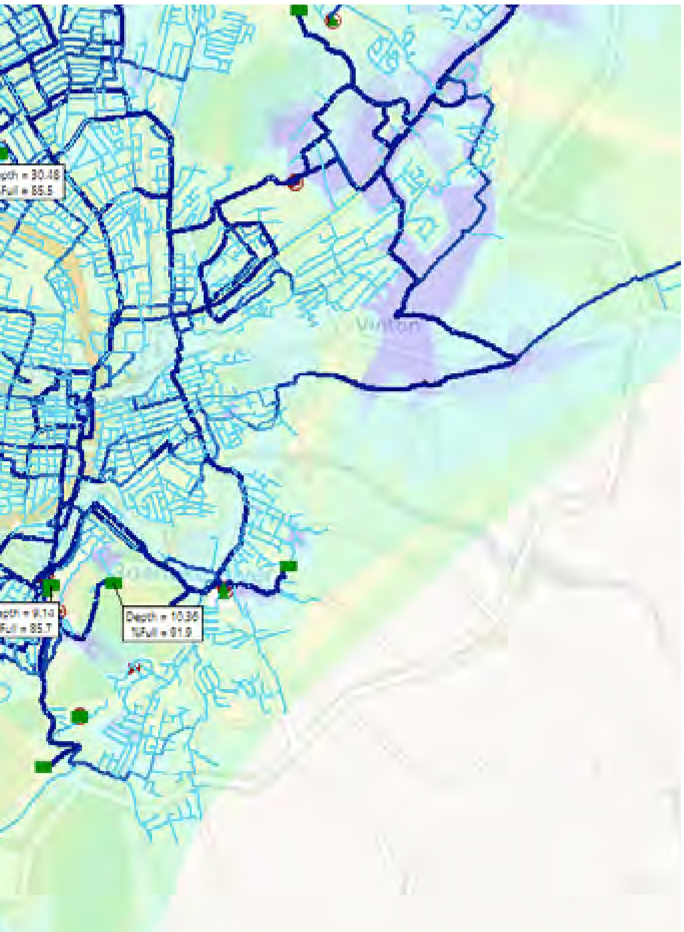
A partnership between Newcastle University and Northumbrian Water Group is developing a digital twin of Newcastle — a computer replica of the entire city.[118] Much of the data comes from the university's Urban Observatory project, which has sensors all over the city monitoring pollution, water quality and biodiversity. Using the digital twin, real-time resilience testing could be run to see how a city's infrastructure would perform in the face of climate change and population growth. In 2012, a month's worth of rain fell on Newcastle in two hours during evening rush hour, causing £8m worth of damage. In future, the digital twin would allow the city to react in real-time to such weather events and to test large numbers of potential future emergencies. It could predict which buildings would be flooded, the infrastructure that would be closed, and the hospitals that could be affected. In time, this model could be applied to any city with accessible data. The project is part of a pioneering initiative by the Rockefeller Foundation to help cities become more resilient to the challenges of the 21st Century.

SWAN H20

A Water Consortium for Digital Twins



The Smart Water Networks Forum has established the Digital Twin H2O Work Group, with the intention of reducing isolation and accelerating the adoption of digital twin technology in the water sector.[119] Its strategy is to coordinate the efforts of utility providers, solution providers, engineering firms, government, and academia. This coordination will give disruptive impetus to the industry, increasing operational efficiency and cutting prices for consumers, while increasing the global availability of water. The consortium is organised into three working subgroups: (1) Holistic Digital Twin Technology Architecture, (2) Outcomes and Applications, which determines priority areas for application of the technology, and (3) Case Studies and ROI Calculations — deriving useful knowledge from digital twin success stories elsewhere, for adoption by the consortium. Organisations may also become observer members, which entitles them to receive various updates from the Work Group. SWAN H20 held its first Workshop in May 2019 and has so far been endorsed by prominent firms including AngliaWater, AVEVA, KWR, GoAigua, Jacobs and VCS Water Denmark.



INNOVYZE

Vision of Digital Twins for the Water Industry

The water industry is currently waking up to the potential of digital twins to orchestrate water supply, wastewater, flood control, networked assets, asset registry, and so on. These elements must be aligned to function together effectively — especially given the imminent supply challenges faced by the industry. Putting operational data at the heart of planning, design and operations will enable the best possible decisions for consumers. For this reason, Innovyze have created a digital twin to aid the design, simulation, management and maintenance of water assets.[120] They aim to integrate their twin with infrastructure assets, modelling and simulating using real-world data streams to optimise performance. In conjunction with InfoAsset Online, their new service, they have opened information from utilities providers to be shared with maintenance crews, contractors, planning departments, regulators and consultants to give them a more complete view of the asset they are working with. The technology is already used by Thames Water (UK), the Smart Tunnel operators (Malaysia), East Bay Municipal Utility District (California), and Sydney Water (Australia) to provide guidance on leakages, flood risks, optimal maintenance, and rehabilitation.

BENTLEY SYSTEMS

Smart Wet Infrastructure

Bentley Systems and Digital Water Works are collaborating to provide digital twin solutions for 'smart wet infrastructure' to municipal and investor-owned water and wastewater utilities worldwide.[121] Wet infrastructure refers to water supply, treatment and storage, water resource management, flood management and hydropower. It also covers locks, weirs, storm-surge barriers, guiding structures, pumping plants, and related structures. Combining real-time intelligence with spatial analytics, the digital twin enables the simulation of water distribution and sewer collection systems, providing visualisation and analytics capability that can be used to detect and isolate deficiencies, perform diagnostics and troubleshoot problems. This geospatial platform enables utilities to operate and sustain more resilient wet infrastructure while maintaining compliance, meeting appropriate levels of service at the lowest total lifecycle cost.

CHAPTER 3

Challenges and conclusions

Any large change to an industry requires overcoming technical, legal, and cultural hurdles. This is particularly true with emerging technologies like the digital twin. New skills and talent must be brought in, new training infrastructure must be created, and cultures must change.

CHALLENGES

Our research has revealed promising advances in the development of digital twins; notably, there have been large investments from governments, organisations, software companies and research entities in recent years. Yet, as with any emerging technology, there are challenges we must overcome – technical, legal, and cultural hurdles, for example. New skills and talent must be brought in, new training infrastructure must be created, and cultures must change. Key risks in the current landscape will need to be considered; these include big data, security and economic returns. Furthermore, this must be done in the face of uncertainty around long-term return on investment, which is where experienced advisors and experts will play crucial roles. We need to be wary of solutions that promise too much, and case studies with little evidence that investments have yielded secure returns. Let us briefly consider the challenges posed by big data and by information security.

We now live in a world where data affects every facet of our lives, which raises the urgent question of what kind of data, and in what amounts, we must collect to achieve our desired outcomes. While data-driven decisions are only as good as the data collected, the answer to this question is not always clear in advance. For instance, how do we collect emotional data of employees and use that data to adjust the environmental parameters of the building, to promote more productive and happier workspaces? How much data do we need from each individual, and can we trust its fidelity once we have it? The designs of and inputs to our digital twins are ever changing, and the twins must adjust to the changing parameters. With regard to data storage, more organisations of all sizes are moving to the cloud for strategic, financial and operational flexibility and scalability. Given this shift, we need to consider how we use, build and operate our digital twins, and how we handle their vital role in the consumption, computation, storage and management of information.

Security and privacy are key for those operating digital twins as well as for those interacting with them. We need to consider data governance, open standards, APIs, privacy, intellectual property and cybersecurity. At present, the information assets of many organisations may not be properly managed and secured, i.e. in a state ready for a digital twin to make use of them. Each organisation will need to develop appropriate policies and practices. With the EU Generation Data Protection Regulation in place, companies are now legally bound to greater accountability, and data collection must be planned accordingly.[122] Location data, for example, is generally highly desirable, and when properly collected can be a major aid in smart city planning and development. However, data anonymisation remains a challenge.[123] A recent study attempted to gauge the ease of retrieving identities from supposedly anonymised data, and found that 99.98% of Americans could be correctly re-identified from their demographic attributes.[124] These results clearly challenge current data protection practices. However, new methods such as synthetic datasets are targeting the problem of anonymisation. True integration remains a challenging proposition, and the successful and secure integration of digital twins will require more research and development before the industry reaches a state of maturity and understanding.

OPPORTUNITIES

There are a number of technologies and trends we must consider when thinking about the evolution and future of digital twins across our markets of interest. These include connected devices, cloud and edge computing, 5G, and autonomous vehicles that may influence how we deliver new products and services. Connected devices are greatly benefiting the built environment, rapidly changing the way we design and offer services. Cloud computing, data and analytics provide insights into assets and their performance, allowing us to take well-informed and timely action. These continuous feedback loops lead to improved products and processes. A better understanding of the relationships between devices, people and civic infrastructure will be critical in advancing the digital twin.

Edge computing is another important technology gaining traction as digital devices continue to proliferate. It involves processing data on the periphery (or ‘edge’) of a network, rather than on centralised servers.[125] The prospect of continuous feedback loops appears challenging at a time when more and more of our data is stored in the cloud, but edge computing can allay these problems by processing data at or near the source of its generation. This approach is critical, for example, where connectivity is poor, or where network latency is an issue. ▶


DYM
DYMOCKS
20

Another technology gaining importance is 5G, whose integration into business will result in higher volumes of data processed at much faster speeds. 5G represents a step change in data transfer capacity, and will introduce very high carrier frequencies with exponentially increased bandwidth.[126] Autonomous vehicles are one prime candidate to benefit from both edge computing and 5G connectivity, which, taken together, will facilitate instant reactivity in an ever-changing physical environment. These technologies will improve the safety and performance of autonomous vehicles. Remote assistance is another new service finding favour in the industry; the idea takes aim at inefficient troubleshooting methods, allowing technicians to address the problem at hand immediately such as indicator notifications on a dashboard. We expect greater adoption of these technologies over the coming years to advance the knowledge and development of digital twins, with many more opportunities for growth and innovation.

CONCLUSIONS

In this report, Arup presents the current state of digital twins and flagship examples of how they are changing the design, engineering, and operations of the built environment. We discuss the definitions of digital twins across the industry and academia while including the notions of autonomy and learning. Furthermore, a working evaluation framework is proposed to help the industry align in its ability to evaluate the sophistication of individual digital twins; these metrics are used to evaluate each of the case studies. We also present a collection of interviews with global experts which give insight into the complex issues around, for example, security, privacy and data longevity as they relate to digital twins.

By reviewing the current state of the digital twin landscape, we are able to elucidate what is still lacking in the typical twin – most obviously, the ability to learn and reason. Our interviews make clear that digital twins are a fundamentally data-driven proposition, and in the world of modern computation, this means that they will inexorably develop towards learning and reasoning. Furthermore, it is clear that digital twins must be user-centred, inclusive of society — the ultimate beneficiary of a digital twin landscape — but also inclusive of those who interface with digital twins explicitly, the decision makers. Simulations and static models alone are not digital twins, as they do not take into account the direct link and feedback from model to real world.
The research clarifies a series of challenges for further research, including issues we have already mentioned such as cybersecurity and privacy, but also less obvious issues such as marketing hype, or the continued challenges of data, which may be inconsistent and sparse datasets. In addition, digital twins require regular maintenance and upkeeping.

While the benefits that digital twins will bring to the built environment are clear to most — predictive maintenance, cost control, and asset optimisation — it is equally important to point out the positive role they can play with regard to sustainability and other societal challenges in the design and engineering of civil infrastructure. In order for this positive role to be realised, we must work and collaborate across disciplines. The vision we emphasise for our industry is the widespread development and adoption of what we term 'level 5' digital twin, whose hallmarks are the abilities to autonomously learn from and reason about their environments. While we are still far from a landscape populated by digital twins at levels 4 and 5, our case studies, interviews and thought leaders give good reason for optimism in this direction.

Ultimately, the evolution of digital twins will help asset owners, managers and society at large to take more informed decisions, on the basis of real-time data. While we currently have widespread autonomy of warning systems, this will turn into widespread predictive systems, and finally into reasoning twins.

CALL TO ACTION

Digital twins have already enabled us to automate many redundant and tedious tasks using machine learning, which has resulted in higher productivity. Soon, we will be able to alleviate the problem of fragmented and isolated data, further benefitting our cities and infrastructure. The digital twin concept is limited by our imagination, rather than by our technology. In the not-too-distant future, we envisage an ecosystem of digital twins communicating across boundaries, sharing data and learning from each other to form meaningful collaborations and solve global challenges. We must build partnerships and foster relationships as we tackle the technological, cultural and societal challenges of digital twins. As we continue to drive forward the development of the digital twin, please stay in touch with us via digital@arup.com.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We are truly global. From 88 offices in 33 countries our 15,000 planners, designers, engineers and consultants deliver innovative projects across the world with creativity and passion.

Founded in 1946 with an enduring set of values, our unique trust ownership fosters a distinctive culture and an intellectual independence that encourages collaborative working. This is reflected in everything we do, allowing us to develop meaningful ideas, help shape agendas and deliver results that frequently surpass the expectations of our clients.

The people at Arup are driven to find a better way and to deliver better solutions for our clients.

WE SHAPE A BETTER WORLD

Digital twin

Arup has started the journey towards digital transformation. Creativity with data at scale, across all aspects of our organisation, is an integral part of our knowledge, practices and culture. As part of this strategy, we are looking at research and collaboration to shape our thinking and partnerships for the future. *Digital Twin: Towards a meaningful framework* is part of our aim to share ideas and develop meaningful relationships.

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