In collaboration with the China Academy of Information and Communication Technology

WORLD ECONOMIC FORUM

Digital Twin Cities: Framework and Global Practices

INSIGHT REPORT

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Foreword

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The continued growth and success of cities is one of the great triumphs of modern civilization. Cities are home to the majority of the world's population and generate more than 80% of GDP. Rapid urbanization has also brought about new challenges as cities have struggled with congestion, pollution, increased carbon emissions, inequity and exposure to natural disasters such as floods and storms. The COVID-19 pandemic and climate change have further intensified these issues.

The United Nations 2030 Agenda for Sustainable Development sets out the goal of "building inclusive, safe, resilient and sustainable cities and communities". Whereas these goals may be universally accepted, the path to get there is not as clear. Innovation and empowerment of digital technology are critical to transforming our cities. Policy support and institutional change are also essential.[1]

The digital twin city is a relatively new concept – it provides a tool for improving urban planning and construction, combining innovations in digital technology with new operational models and approaches for re-imagining the built environment. Through the precise mapping, integration and interaction of real and virtual environments, digital twin technology presents the opportunity for safer, more efficient cities, more convenient and inclusive everyday services, and a reduced environmental footprint. An increasing number of cities around the world, such as Xiong'an, Singapore and Rennes, are advancing such practices with promising results.

The China Academy of Information and Communication Technology (CAICT), a national think tank in China, has long been committed to research and innovation in the field of information and communications. Based on digital twin research, CAICT's Smart City Team proposed the innovative concept of the "digital twin city" in 2017, discussing with industry experts and academics how best to promote the development of digital twin cities and the sharing of related methodologies.

Digital Twin Cities: Framework and Global Practice is the result of research conducted by CAICT's Smart City Team and the World Economic Forum's Urban Transformation partners. The report proposes four technical features, three visions and nine key elements driving the development of digital twin cities, as well as ideas and recommendations for building high-quality digital twins in response to current challenges. The paper has implications for city managers around the world who are exploring digital twin city construction, and for entrepreneurs and investors who are actively embracing digital twin technology and promoting its application.

In the future, CAICT aims to work with the World Economic Forum and global industry multistakeholders to promote deeper research on global digital twin city theory, publish guidelines for the construction of digital twin cities, build an online case library, share technological innovations and practical experience, and help deliver digital twin cities with a more people-oriented and sustainable focus.

Executive summary

More than half of the global population lives in urban areas. As a result of the rapid growth in the rate of urbanization, cities face huge challenges in meeting the housing, infrastructure, transport and energy needs of their urban populations, and urgently require new ideas and methods to solve these issues.

The purpose of urban transformation and sustainable development must be to enable people and nature to flourish together for generations. This requires a shift in focus from merely creating the built environment to improving the outcomes enabled by it – the city must be outcomes-driven for people and place. Urban systems must come together to help deliver those outcomes because cities are served by complex systems of interconnected assets and networks. They are a "system of systems".

The key challenges of our generation are also systemic: achieving net zero, climate resilience and the circular economy are systems-level challenges that demand systems-based solutions. Therefore, our cities need systems-based policies, strategies and tools that enable us to understand and manage the urban transformation to achieve its purpose.

Fourth Industrial Revolution technology – represented by the digital twin approach, together with policy and mechanism reform, which help us to understand systems better and intervene more effectively – is being used by cities to reshape and optimize their urban planning and operations, governance and service models, and planning method. This allows them to upgrade iteratively. Managing the city as a system of systems with a focus on delivering better outcomes for people, society and nature requires integration across the industries that serve the built and natural environments. It also requires us to connect the physical, digital and human worlds.

Digital twin cities have already been put into practice in Singapore and Xiong'an, China, where they have been used to improve urban public services and management, assist the government in providing urban services more conveniently and efficiently, and use 3D modelling to promote more accurate city governance on the ground. However, the development of digital twin cities is still in the primary phase. It faces many challenges, such as fragmented understanding, immature technology and unclear business models. There is an urgent need for all parties, from industry leaders to academics and those working in research and application, to discuss and gradually reach a consensus on the implications and architecture of the digital twin city, sharing best practices to ensure the digital twin city develops effectively.

The digital twin city maps the physical city in the digital space through the construction of a virtual version of the city. Its goal is to: 1) solve the complexity and uncertainty of urban planning, design, construction, management and services through simulation, monitoring, diagnosis, prediction and control; and 2) establish the simultaneous operation of and interaction between the physical and digital dimensions of the city. The digital twin city has four typical technical features: 1) accurate mapping; 2) analytical insight; 3) virtual-real interaction; and 4) intelligent intervention.

The digital twin city pursues three visions: 1) more intensive and efficient urban production and operation; 2) liveable and convenient urban living spaces; and 3) a sustainable urban ecological environment. In terms of urban production, digital twin technology is used to make an intelligent analysis of complex scenarios in terms of the flow of people, goods, energy and information. Examples include optimizing urban spatial layout, relieving traffic congestion at complex intersections, simulating and rehearsing responses to natural disasters, and scientifically formulating emergency evacuation plans. The goal is to generate insights into urban operational patterns, reduce governance costs and improve citizens' quality of life. In urban life, digital twin technology is used to monitor the performance of urban components, predict failures and avoid risks, and ensure the safety of residents. With the help of digital twin technologies, hospital, classroom and community services can be created using virtual-real interaction and customization. In terms of emissions reduction, digital twin cities can help city managers and experts to: 1) evaluate and optimize ecological features; 2) make a comprehensive diagnosis of various carbon emission implementation policies and select optimal solutions; and 3) promote the efficient operation and maintenance of energy facilities and carbon trajectory tracking. These measures can help cities achieve carbon neutrality.

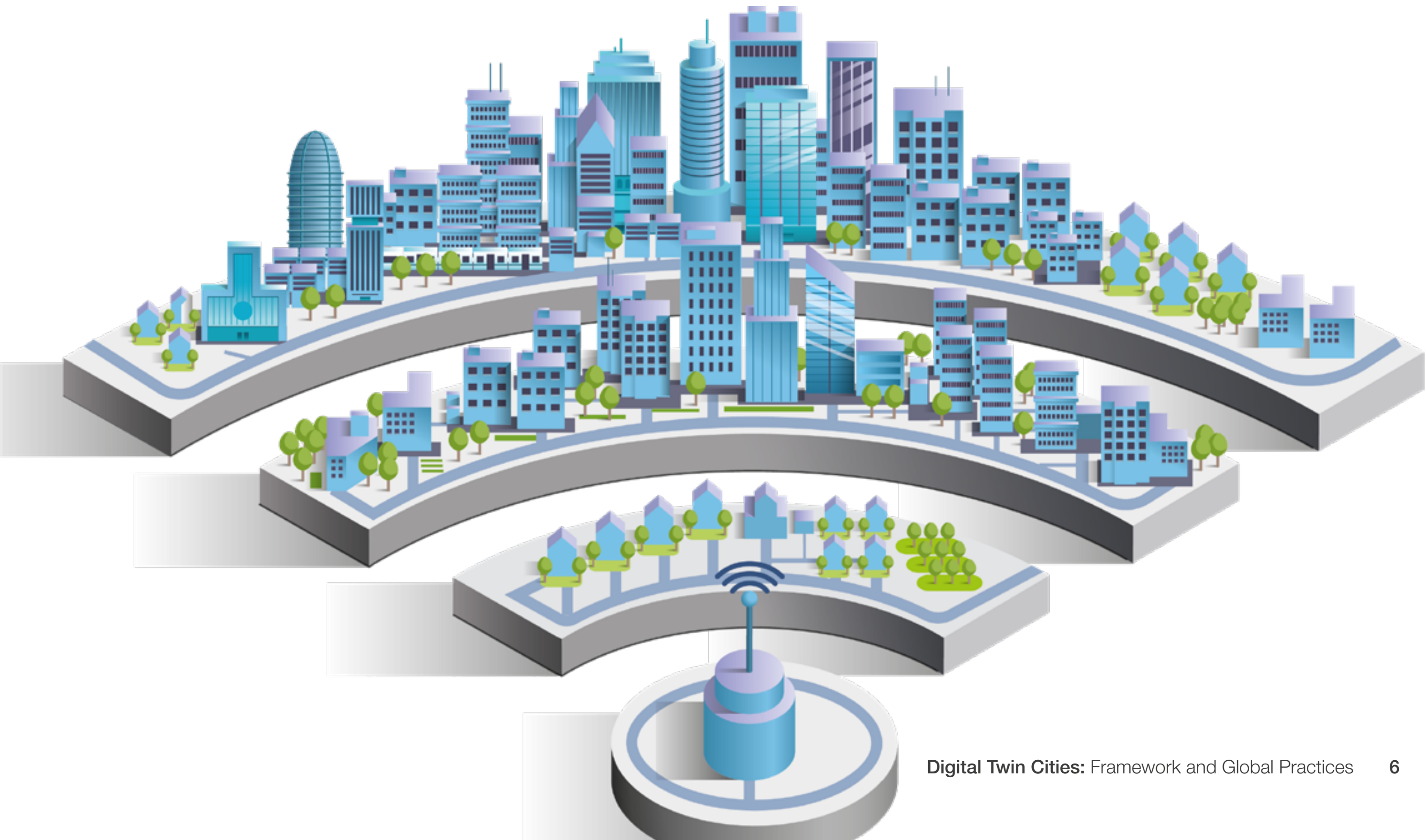
Developing a digital twin city requires nine elements, representing a "4+5" framework. The "4" refers to the four core elements, which are: 1) Infrastructure; 2) data resources; 3) platform capacity; and 4) application scenarios. These elements provide the internal power and digital base for the digital twin city. The "5" in the framework comprises the five major external supporting elements of digital twin cities. These are: 1) strategy and mechanisms; 2) stakeholders; 3) funding and business models; 4) standards and evaluation; and 5) cybersecurity.

At present, the construction of digital twin cities still faces many challenges. Understanding of the approach and perception of its value are not widely shared. Furthermore, the increased use of data heightens the risk to digital security and privacy protection, there is a lack of interdisciplinary human resources and industry knowledge resources, and innovative business models still need to be developed. According to original research, 66.7% of digital twin city projects are currently funded by governmental investment; therefore, social capital and enterprise investment still need to be improved.

Technical solutions are clearly necessary, but they are not sufficient; technology needs to be developed in a human-centric manner. The ultimate goal of digital twin cities is to promote social equity and inclusiveness; protect individual rights and the positive business power that transforms cities; empower both the weak and the strong; render the city more liveable; and build harmony among people, city and nature. For a city-level connected digital twin programme to be successful, it must also address human and organizational factors. It must address: ethics and skills; and commercial, legal and regulatory solutions. Nowhere is this clearer than in enabling data-sharing across organizational boundaries, but it is equally important in the basic hard work of driving an increase in information management maturity in every organization. This is why a connected digital twin programme must be "socio-technical". This ensures each organization benefits from improved decision-making and enables connected digital twins to deliver better outcomes across the economy. In short, a socio-technical change programme for connected digital twins is the route to better outcomes for people, society and nature.

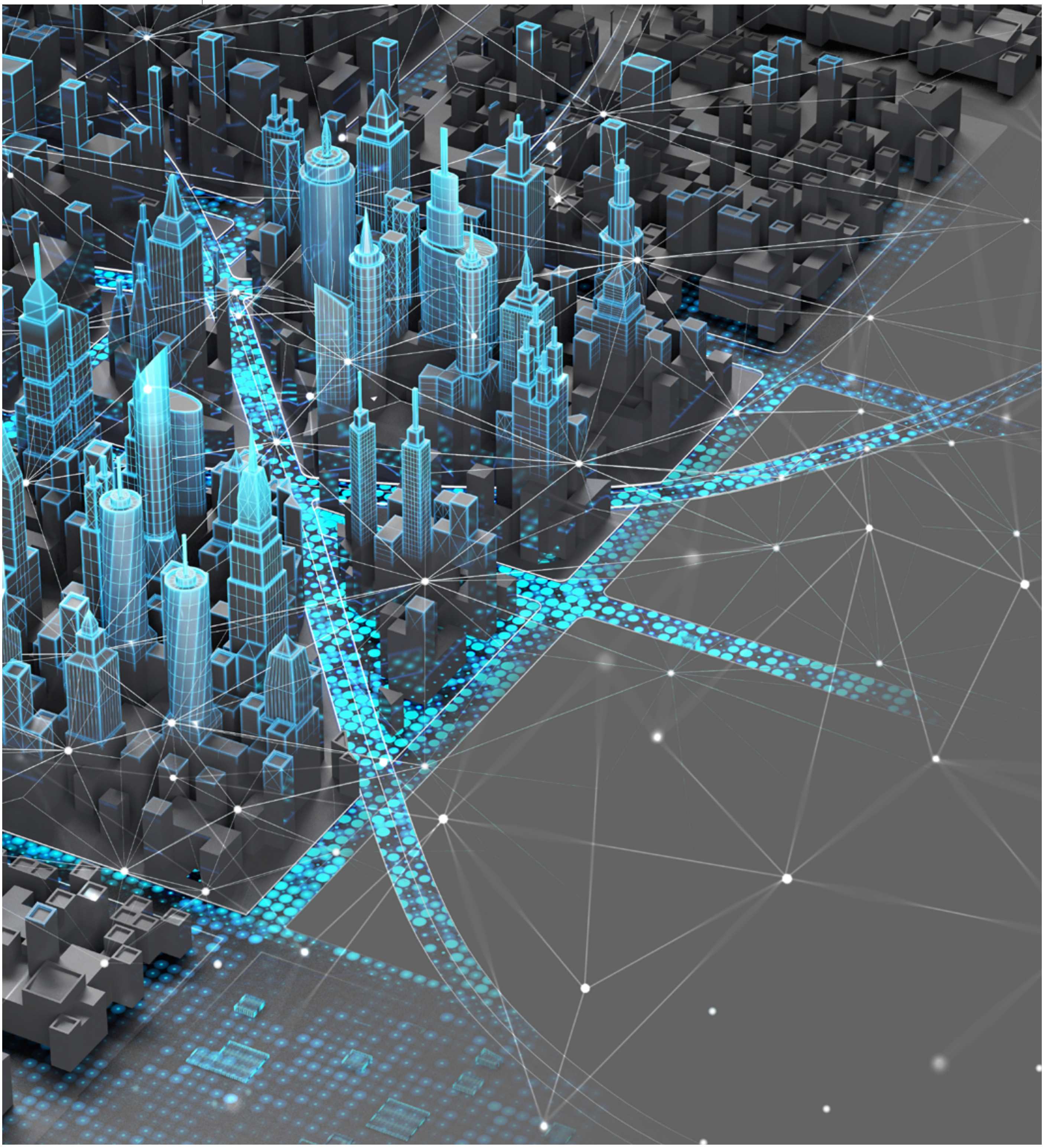
Looking ahead, the effective development of digital twin cities needs to be promoted by governments, enterprises and other relevant stakeholders. Governments should: 1) fully coordinate top-down top-level design with bottom-up grassroots demand, and stimulate the motivation of citizens and organizations to innovate; 2) design more cross-industry digital twin scenarios around individual demand, tracking supply with demand; 3) build a twin-city data system with hierarchical classification to ensure distributed security and personal privacy protection; and 4) build a multidisciplinary and comprehensive talent team for collaborative innovation. Enterprises should: 1) make it easier for small and medium-sized enterprises (SMEs) to participate by lowering the barriers to apply; 2) forge a unique advantage in the digital twin field and create a prosperous innovation ecosystem that combines all respective strengths; 3) focus on industrial implementation standards to form a standardized partnership of interconnection and mutual benefit among industrial actors; and 4) expand the digital twin city from the to-government ("to G") market to the to-business ("to B") and to-customer ("to C") markets, and transform projects from one-time construction into long-term cooperation covering operation and service purchasing.

Digital twin technology is a new way of thinking and an advanced form of technological power. For such technology to progress in the long term, multistakeholders will need to cooperate and work together to ensure that the important role of digital twin technology is recognized, and that it is understood and disseminated. Also required are the mapping and exploration of the digital twin governance framework and the building of a consensus around it. Finally, success calls for the incubation, support and standardization of application scenarios.



1 The concept and value of the digital twin city

Cities are becoming the core drivers of rapid economic and social development.



Although they serve as innovation centres, cities also face increasingly serious challenges such as weak economic recovery, carbon reduction targets, emergency and disaster prevention, and surging demand for medical services and elderly care. The United Nations has proposed 17 sustainable development goals (SDGs) to be achieved by 2030, among which the establishment of "sustainable cities and human settlements" (Goal 11) relies on digital technology innovation and the support of policy-makers. With the development of the Fourth Industrial Revolution, the path of urban development and transformation – where digital technology is the main driver and data is the core means of production – is becoming increasingly clear. Digital twin technology is becoming a bridge between the physical and digital worlds.

1.1 The digital twin city concept is becoming clearer

The United Nations has proposed 17 sustainable development goals to be achieved by

2030

Nearly 20 years in development, digital twin technology is used not only in the manufacturing industry but also in many other industries and in public life. The concept of the digital twin city, a new model of urban development and management based on digital twin technology, is gradually becoming clearer.

In 2002, the Information Mirroring Model concept was first proposed to depict the concept of the digital twin. In the Mirrored Spaces Model, introduced by Professor Michael Grieves at the University of Michigan in 2006, a set of digital models is constructed in the virtual space to interact with physical entities and fully describe the trajectory of physical entities throughout their life cycle.[2]

The definition of a "digital twin", first established in 2012, has since been widely applied in industry. Inspired by NASA's Apollo programme, NASA researchers E.H. Glaessgen and D.S. Stargel defined the digital twin as the integration of multidisciplinary and multiscale simulation processes by making full use of physical models, sensors, operational history and other data. The digital twin acts as a mirror image of the physical product in virtual space and reflects the full life cycle of the physical entity.[3]

In 2017, the concept of a "digital twin city" was first proposed by CAICT and used in the planning and construction of smart cities. Based on the information technology systems of digital identification, automated perception, networked connection, inclusive computing, intelligent control and platform services, a digital city matching the physical city is recreated in the digital space, with holographic simulation, dynamic monitoring, real-time diagnosis and accurate prediction of the state of the physical city entity in the real environment. This helps promote the digitalization and virtualization of all elements of the city, a real-time visualization of the entire metropolis, and intelligent and collaborative urban operation and management. As a result, the physical and virtual cities can be engaged in synergistic interaction and parallel operations.[4]

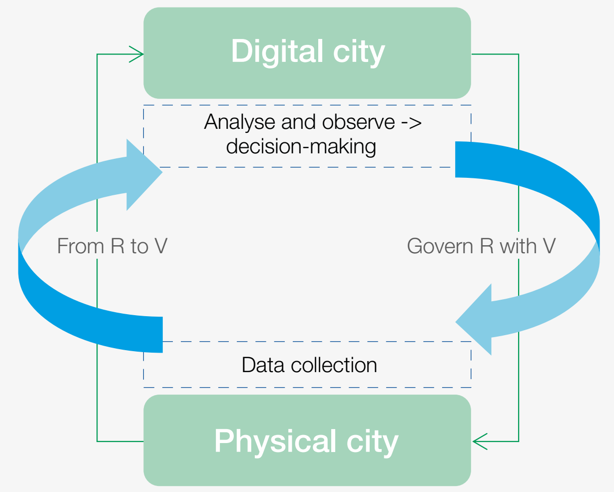
Also in 2017, the concept of "smart city digital twins" was proposed. From the perspective of an urban platform, the Georgia Institute of Technology proposed that the digital twin of a smart city is an intelligent, internet of things (IoT)-enabled, data-rich urban virtual platform that can be used to replicate and simulate changes that occur in real cities in order to improve the resilience, sustainability and liveability of cities.[5]

In 2018, the "five-dimensional digital twin model" was proposed and constructed. Professor Tao Fei of Beijing University of Aeronautics and Astronautics proposed the five-dimensional model, which embodies physical entities, virtual entities, service, twin data and connections. He argued that the purpose of digital twins is to digitally create a virtual model of a physical entity, simulate the behaviour of the physical entity in the real-world environment with the help of data, and add or extend new capabilities to the physical entity by means of virtual-real interaction feedback, data fusion analysis and iterative optimization of decision-making.[6]

Since 2019, the concept of a digital twin city has been widely promoted and generally accepted. The digital twin city is a new application model of the "digital twin" concept in smart city construction – that is, recreating a complex, giant system in digital space that maps and interacts with the real world to realize the interaction between the physical and digital dimensions of the city.

The digital twin city operational mechanism contains the following steps. First, through IoT, information modelling and a ubiquitous network, real-time data about traffic, the ecological environment and urban operations is collected, making it possible to connect and map from reality to virtuality. Second, based on the knowledge map of a city's operation patterns and big data analysis algorithms, problems in the digital space can be analysed and scientific guidance established for policy-makers. Third, through the remote control and interactive interface of the IoT, the real city can be controlled by a virtual mechanism and establish: 1) the whole life-cycle management service of the physical city; 2) the optimization and improvement of the city's operations; 3) and its sustainable economic development.

FIGURE 1 Operational mechanism of digital twin cities



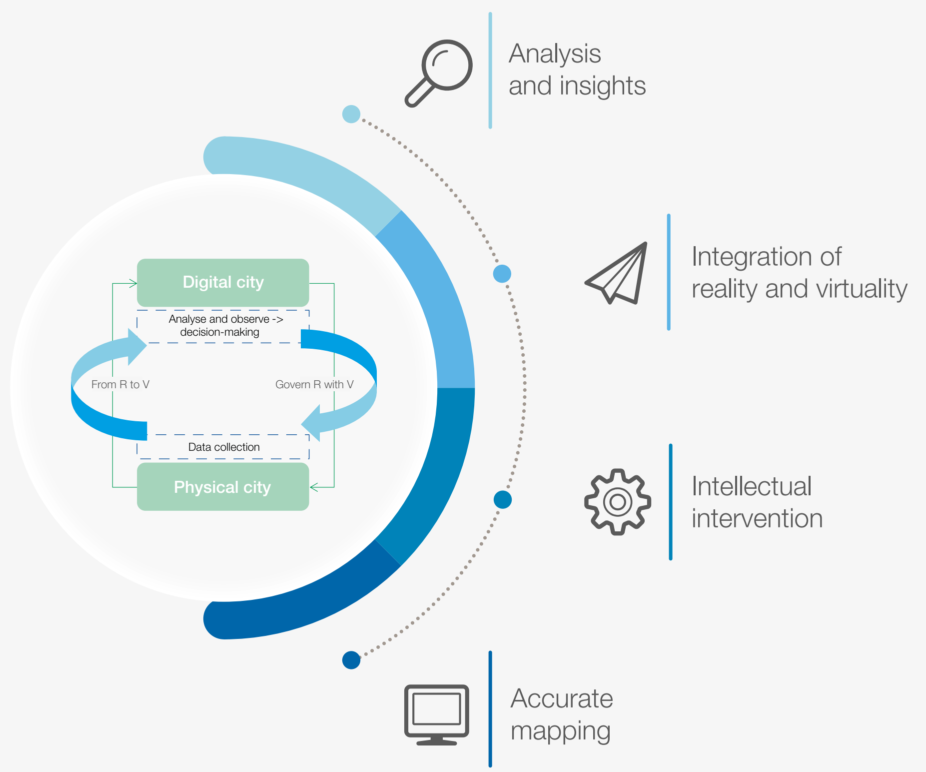
Source: China Academy of Information and Communication Technology

Note: Note: V = virtual; R = reality

1.2 The four major technical characteristics of the digital twin city

Figure 2 depicts the operational mechanisms of the digital twin city, showing that it typically has four technical features: 1) a precise mapping of the physical city and digital city; 2) analysis of and insights from the digital city; 3) the virtual-real interaction between the digital city and physical city; and 4) the intelligent application of insights from the digital city to the physical city.

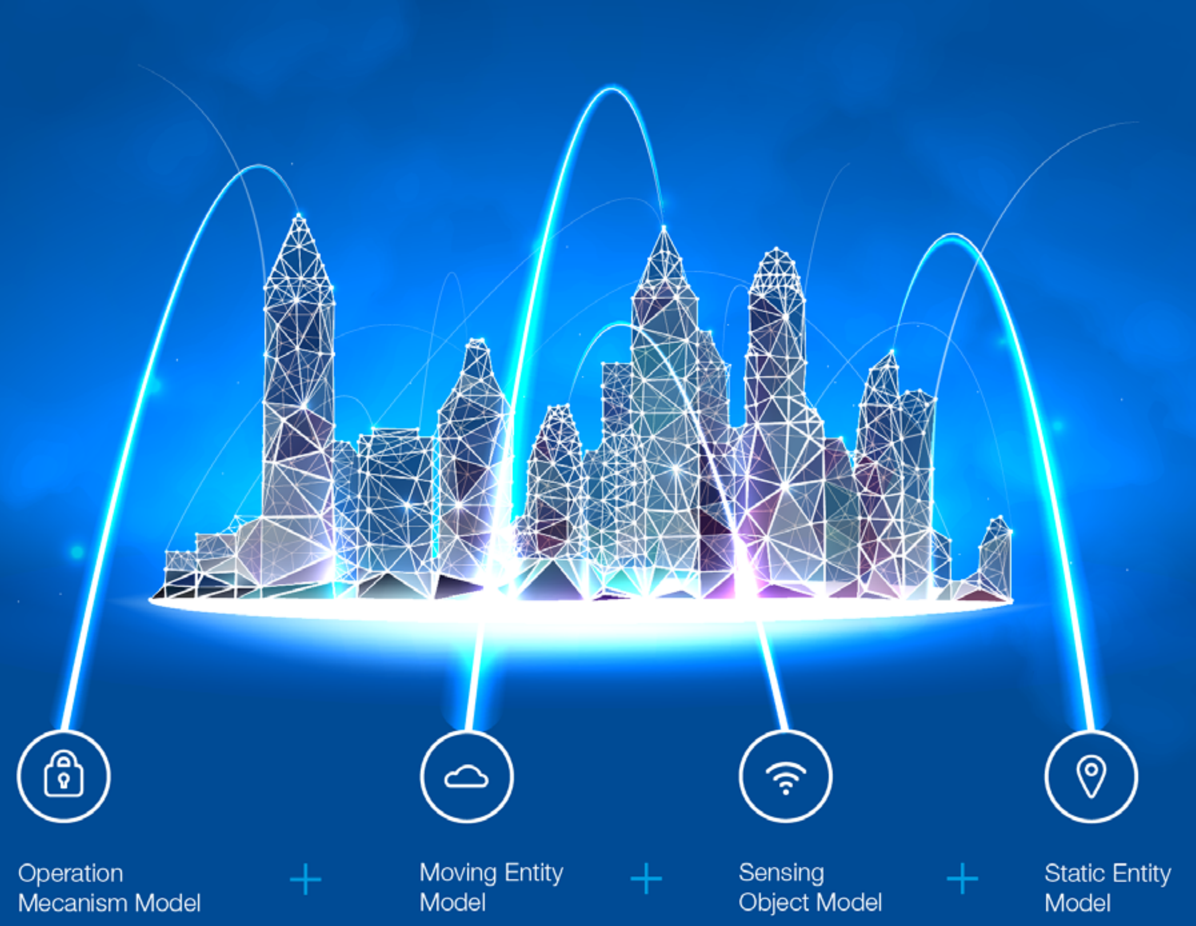
FIGURE 2 Technical characteristics based on the operational mechanism of digital twin cities



Source: China Academy of Information and Communication Technology

Precise mapping of the physical and digital city. Through the use of technologies and techniques such as IoT technology, geographic information system (GIS) and building information modelling (BIM), the digital twin city can present a full picture of physical city operations in multiple layers and scales, including static geographical entities such as buildings, roads, vegetation, water systems, urban components and pipelines, as well as transitory elements such as people, vehicles, devices and organizations.

FIGURE 3 **Precise mapping of the physical and digital city**



Source: CAICT

Analysis of and insights from the digital city. In the digital space, based on the convergence and integration of data collected from the physical city, it is possible to analyse factors such as city congestion, buildings' energy consumption, urban planning and underground pipelines. As a result, city planners are able to understand the risks of city operations and present real scenes through digital simulation, which can guide them to improve the city's logistics by, for example, modifying the timing of traffic lights, controlling high-power consumption facilities, changing site selections and forming relevant strategies for the city's improvement.

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The digital twin city will realize the intelligent operation, control and management of the physical city in cyberspace. It is necessary to grasp the application of the digital twin city, and promote the upgrading and modern governance of the city.

Li Deren, Chinese Academy of Sciences and Chinese Academy of Engineering

INSIGHT AND ANALYSIS CASE

Virtual Singapore platform for urban environment improvement and optimization

The Virtual Singapore platform integrates data regarding ambient temperature and sunlight exposure throughout the day. This enables city planners to visualize the heat island effect in urban areas as well as the effects of any potential measures taken in response. For example, through virtual simulation, city planners can see how measures such as installing "green" roofs and increasing air ducts could adjust the regional temperature and light intensity.

Such virtual simulations help city planners adjust the location, height and shape of buildings in real life to create a more comfortable and cooler environment for residents. In addition, the platform can overlay charts such as noise maps and energy consumption heat data at any time to perform analytical simulations and calculations. The results of these simulations and calculations are used to specify measures to improve the environment.

The virtual-real integration of the digital city and the physical city. By creating a digital twin city, the physical city is enriched, extended and expanded in digital space. For example, city managers can interact with the physical city on the digital platform interface to search specific entities, select 3D spaces for statistical analysis, change the city layout and simulate changes in various urban indicators such as those relating to congestion and ecology. Through virtual reality, residents can follow distance-learning classes as if actually present in a classroom or laboratory and can embark on travel to distant destinations without actually leaving their homes.

FIGURE 4

Real-time interaction and access to education services using virtual reality glasses

Source: AWE (Augmented World Expo): http://www.bieleng.com/post/47995.html

> **Digital twin technology provides for smart cities a bridge between reality and virtuality, as well as an interface for human-computer interaction. This could realize accurate digital modelling of the physical world, efficiently present massive dynamic information about the city, and counter-control the behaviour of the physical world by the resolutions generated by data analysis.**
>
> Yu Zheng, Vice-President of JD Group, IEEE Fellow and Distinguished Scientist of the American Computer Society

The intelligent application of insights from the digital city to the physical city. In the digital space, the digital twin city platform can present the status of city operations in real time. If an accident, disaster or other emergency occurs in the physical city, city managers can make decisions efficiently to deploy corresponding measures. In addition, the platform can also be used to predict the possible problems or risks of the city through deep learning and simulation. Once problems and risks are predicted, they can be prevented in order to reduce property losses and protect people's safety.

SMART INTERVENTION CASE

Digital twin smart fishery delivers unmanned aquaculture

The digital twin fishery can fully present the marine environment through 3D modelling (3Dmax), IoT, GIS and other technologies, allowing aquaculture personnel to perform seawater tests and marine environment simulations, as well as remote controlling aquacultural equipment via the digital platform. Such measures enable them to conduct smart adjustment of water quality and environmental parameters, smart processing of food placement and smart alert of aquacultural information. This could lead to a 50% reduction in operation and maintenance personnel input and a 50% increase in aquacultural production.

FIGURE 5 | **Digital twin smart fishery**

Source: DIGITWIN

1.3 Digital twin technology: bringing great value to cities

The digital twin helps cities reduce costs and increase innovation. First, digital twin technology allows both "what if" and "best possible" scenarios to be run to determine the available strategies that could maximize profits. Second, digital twin technologies could optimize resource allocation and perform intelligent analysis of key actions in the production cycle such as resource allocation, and product processing and circulation. It is predicted that by 2024, more than 25% of new IoT business applications will be bundled with digital twin capabilities.[7] Policy based on such analysis could contribute to the more efficient and rational use of resources. Third, digital twin technologies could reduce the cost of urban innovation; the digital twin city model could also be used as a cloud service for enterprises and citizens to improve urban innovation.

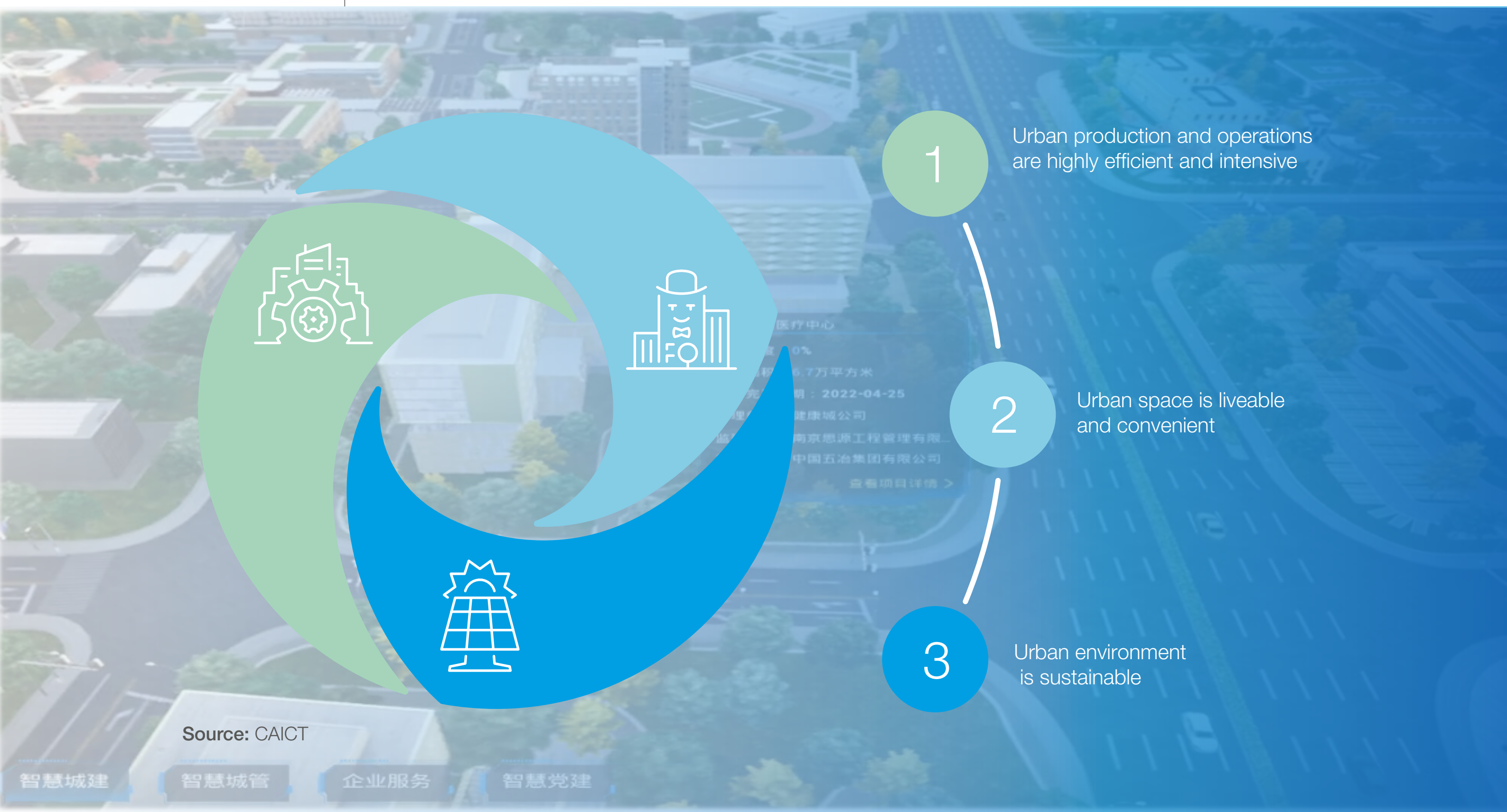
Digital twin technology could significantly improve residents' quality of life and enhance the inclusiveness of cities. First, it enhances citizens' sense of happiness. Through the integration of virtual and real, as well as by integrating multiple possible scenarios, digital twin hospitals, classrooms and nursing homes could provide full-range, full-time, customized services and follow-up services for individuals, thus optimizing their experience. Second, digital twin technology could protect citizens' personal safety and improve the safety and reliability of city operations. Digital twin cities could help test the function of assets and equipment through simulation to predict failures and avoid risks, which is conducive to residents' safety. Third, the digital twin city platform provides virtual and 3D spaces for all age groups, allowing the general public to enjoy these services and share in the digital dividends.

Digital twin technology helps to continuously optimize the ecological environment and improve the resilience of cities. First, it could lower energy costs. According to an infoobs.com survey, a virtual power plant project in an industrial park of Germany can reduce 630 tons of CO_2 emissions per year and reduce the total energy cost of the park by 4.2%.[8] Second, it could help optimize the ecological layout of cities. Through digital twin technologies, experts or city managers can compare and evaluate multiple urban planning programmes or strategies through virtual simulation, perform real-time calculations of ecological indicators and select the optimal scheme for their situation.

1.4 Three visions for the digital twin city

In the digital space, planners can freely edit urban entities to improve city layouts, perform graphic derivations to demonstrate the effects of urban decisions, implement timely interventions via remote control of urban equipment and inspect risks and problems in advance to generate quick responses. As a result, urban production and operations can be more intensive and efficient, urban living spaces can be more liveable and convenient, and urban ecological environments can be more sustainable.

FIGURE 6 **Visions of the digital twin city**



Source: CAICT

We should respond to climate change, support zero-carbon development and build more efficient and resilient cities by enhancing the benefits of digital twin technologies.

Jeff Merritt, Head of Urban Transformation; Member of the Executive Committee, World Economic Forum

Urban production and operations are intensive and efficient. In the digital twin city, the transport of hazardous chemicals can be modelled, the operational effectiveness of underground pipelines can be tested, and the projected effects of natural disasters can be presented in real time. In extreme manufacturing environments such as those with high temperatures, humidity and other risks, digital twin technologies help attain "zero damage" by making it possible to replace human labour with machines and enabling remote inspection and remote control. Digital twin technologies can also help city planners carry out digital design in a quick and convenient fashion, allow city builders to dispatch resources and monitor progress remotely, and enable city managers to analyse and deduce the effects of policy decisions at any time, anywhere. As a result, the overall efficiency of city operations is improved, and labour input, material input and urban energy consumption are significantly reduced, forming a greener, more intensive and more efficient development model.

In mega cities like Hong Kong, Singapore and Shanghai, digital twins have become an indispensable function of city planning and one of the new-generation public services.

Simon Huffeteau, Vice-President of International Infrastructure and Cities, Dassault Systèmes

Urban living spaces are liveable and convenient. In the digital twin city, residents can visualize urban congestion in real time, allowing them to adjust their travel plans. They can also “go sightseeing” to any of the world’s tourist destinations regardless of where they are in reality. It is possible, too, to participate in all sorts of educational experiences, such as physics and chemistry experiments, through virtual reality technology, receive real-time alerts should an emergency or disaster arise, provide feedback on individual needs and urban problems at any time, and follow up on the resolution to these problems. The differences between online and offline experiences can be minimized, with public services such as medical care and education able to benefit more people through the digital twin city.

The digital twin city solves the two conundrums facing smart cities: technical integration and business synergy. Technically, the digital twin solves the problem of scattered or weak integration experienced in traditional smart cities, and business-wise, ‘model+data+software’ constitutes the digital base of the future city, enabling synergy across business lines.

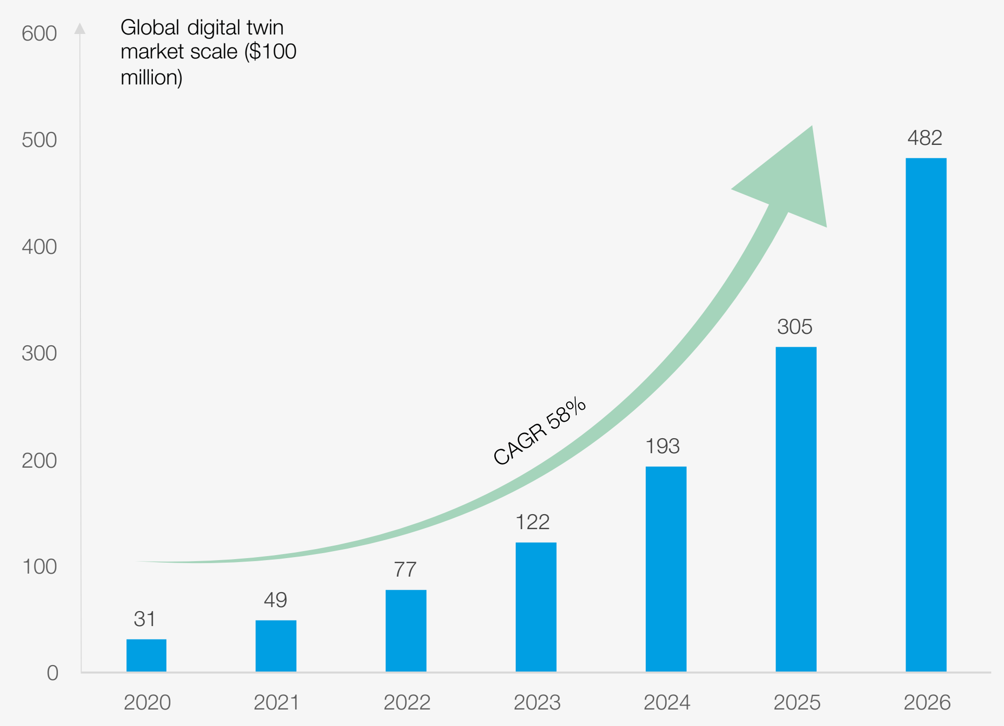
Gao Yanli, Smart City Chief Expert, CAICT

The urban environment is sustainable. In the digital twin city, city managers can learn about the heat island effect, environmental pollution, climate change, energy use and other real-time conditions dynamically, analyse the gap in resource allocation among different regions, and automatically make policies that could optimize the flow and matching of resources. For example, urban green-area planning could be conducted quickly according to the heat island effect, while infrastructure deployment density and signal timing could be dynamically adjusted and planned according to population density and traffic conditions. As a result, the environmental carrying capacity could be greatly improved, the layout of urban resources could be more carefully considered, and urban development could become more sustainable.

1.5 A promising future for digital twin cities

The global digital twin market is booming. It is predicted that by 2030, the application of digital twin technology will save $280 billion for urban planning, construction and operations.[9] In terms of market size, the digital twin market is expected to reach $48.2 billion by 2026 and grow at a 58% CAGR (compound annual growth rate).[10]

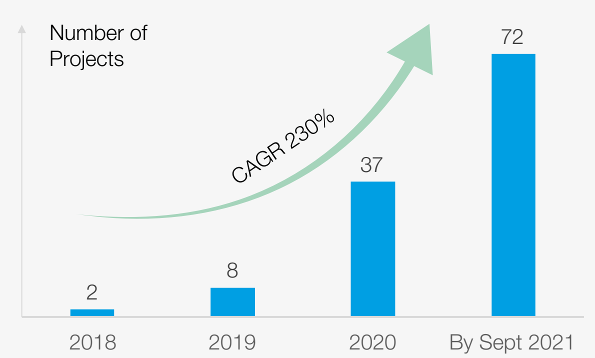
FIGURE 7 **Prediction on the market size of global digital twin cities**



Source: Marketsandmarkets, collated by CAICT

China's digital twin city construction market has great vitality. According to statistics, the total investment scale of China's new smart cities in 2020 was about RMB 2.4 trillion ($0.38 trillion).[11] In particular, China's City Information Modelling (CIM) construction projects have shown a trend of rapid growth year on year, with the number of projects growing from two in 2018 to 72 in 2021 (as of September 2021), and the total amount of investment also climbing year on year accordingly. In August 2021, the World Economic Forum and the CAICT jointly solicited digital twin city cases. According to the data collected for this project, more than half of projects were invested at the RMB 10 million ($1.6 million) level, 89% were invested at the RMB 1 million level or more, and the average investment of the projects reached RMB 28 million.

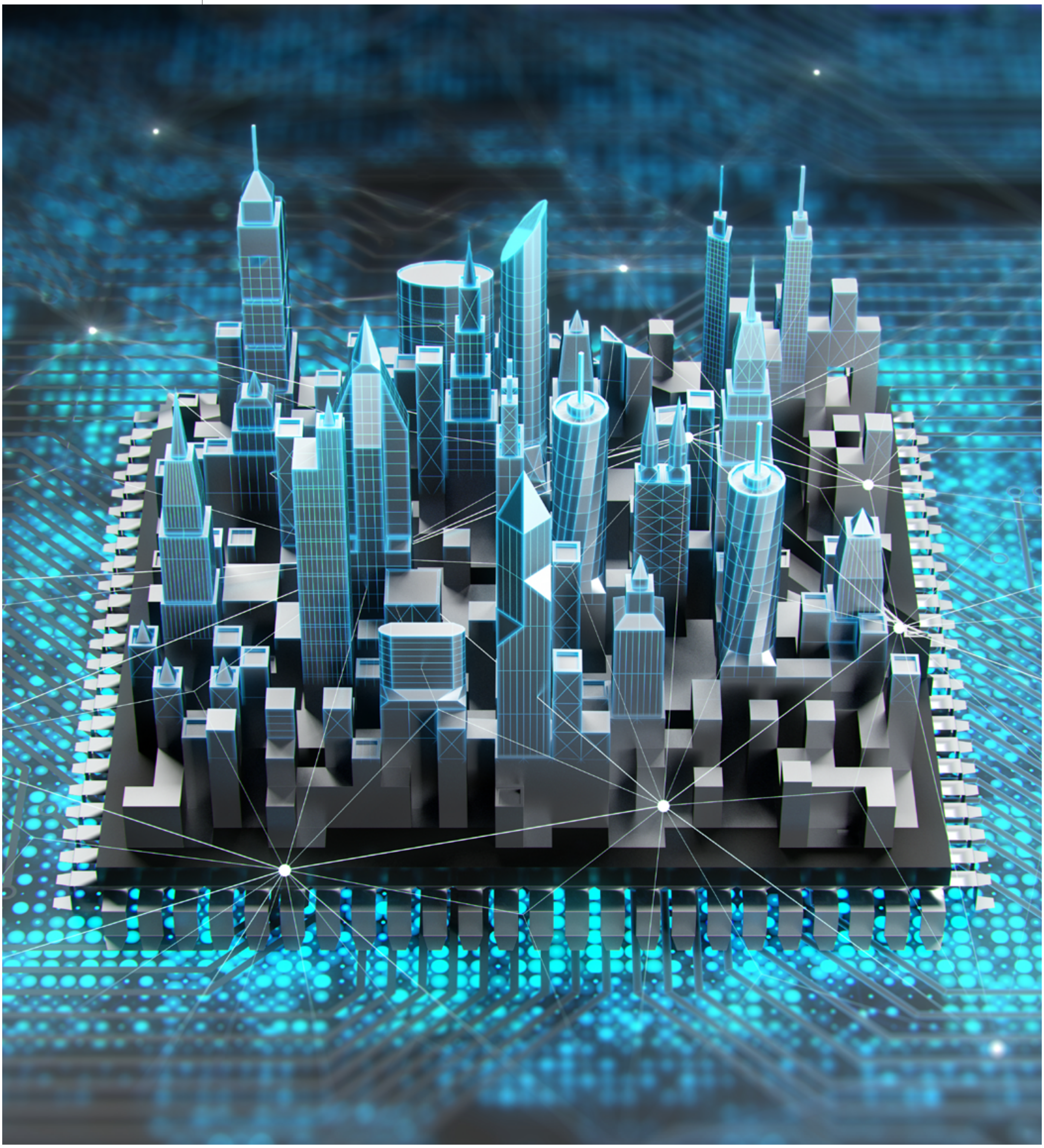
FIGURE 8 **Number of CIM-related tenders and bids by year**



Source: Collated by CAICT

2 Key elements of the digital twin city

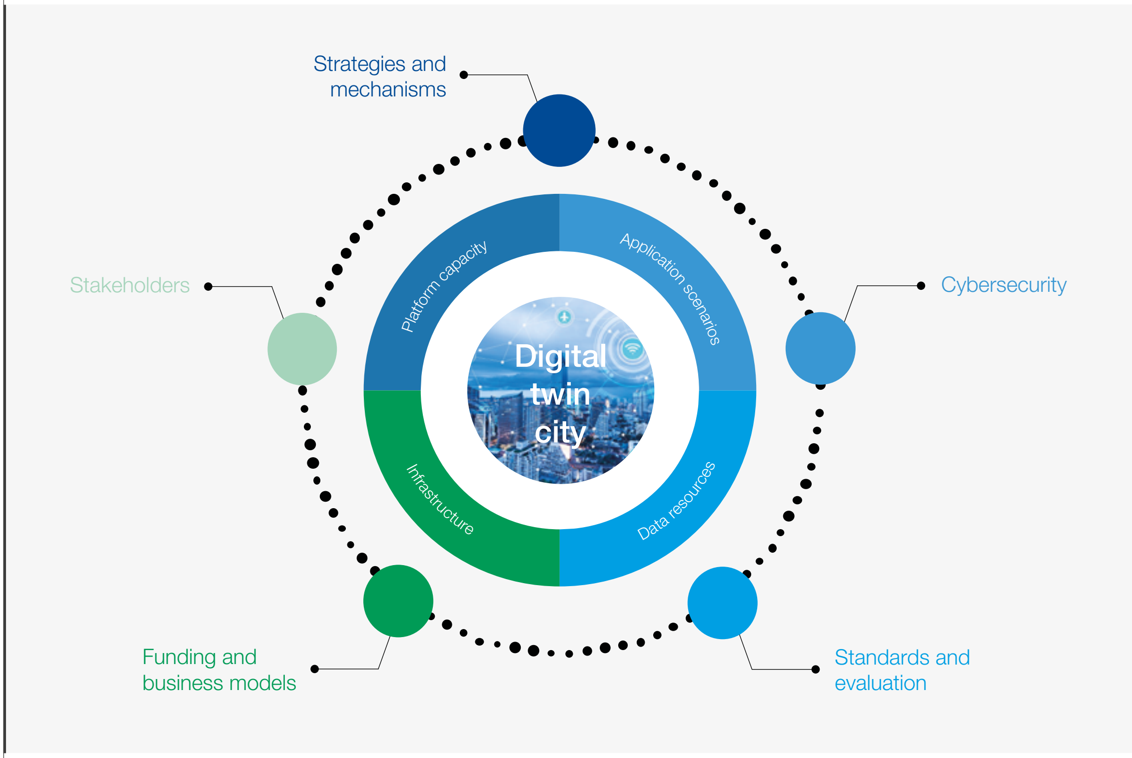
The report outlines nine key elements, in a "4+5" framework, for digital twin city construction.



2.1 Architecture of digital twin city elements

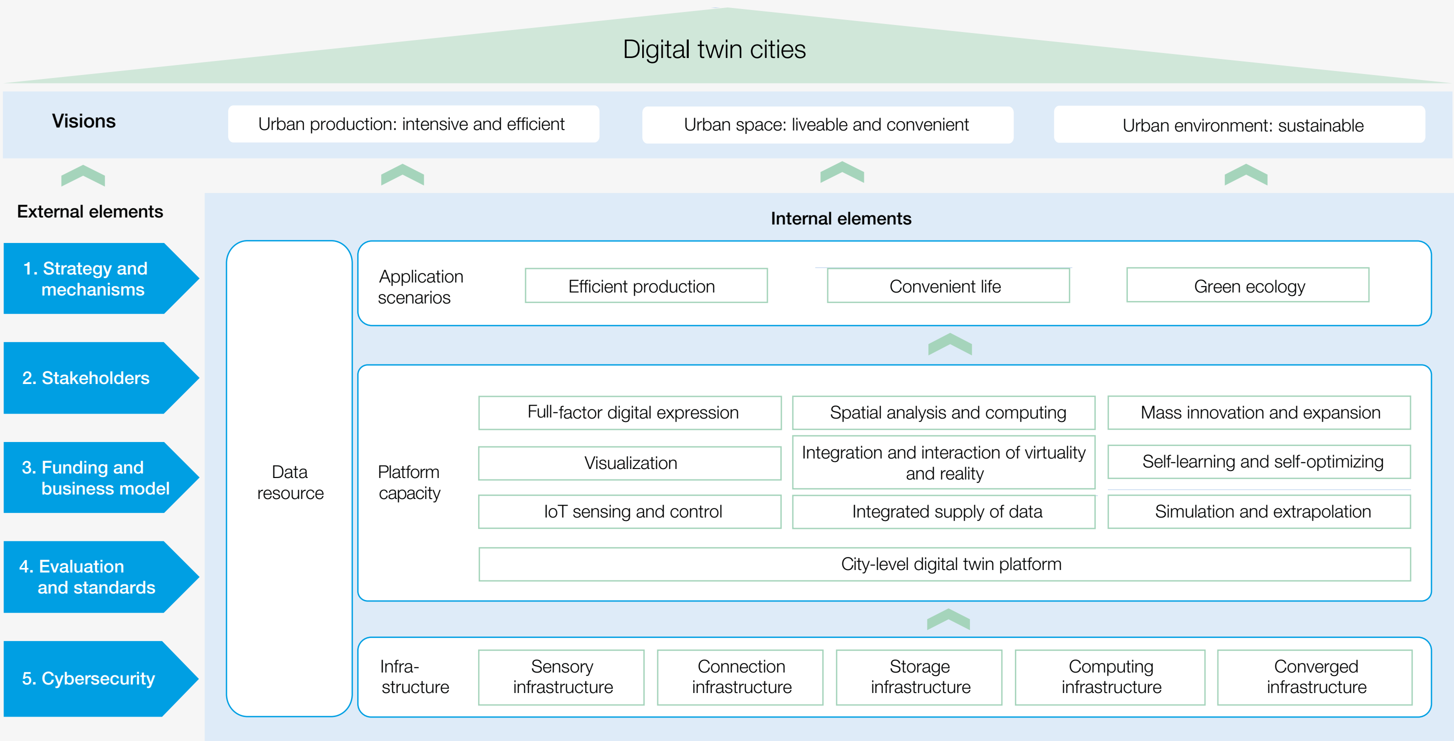
Combining previous research in the field with practical digital twin city examples, this report proposes that digital twin city construction covers nine key elements, presenting a "4+5" framework. This framework includes four core elements: 1) infrastructure; 2) data resources; 3) platform capacity; and 4) application scenarios. It also incorporates five external elements: 1) strategy and mechanisms; 2) stakeholders; 3) funding and business models; 4) standards and evaluation; and 5) cybersecurity. (See Appendix 1 for details of global research perspectives on digital twin elements.)

FIGURE 9 **Architecture of digital twin city elements**



Source: CAICT

FIGURE 10 **Element view of the digital twin city**



Source: CAICT

2.2 Internal core elements of the digital twin city

Infrastructure

The digital twin city is an important means to promote the development of China's smart society. It is necessary to promote the deep integration of communication and navigation, grasp the developing opportunity of the new infrastructure "BeiDou + 5G", and promote the construction of the digital twin city.

Deng Zhongliang, The China Science Center of International Eurasian Academy of Sciences

The information infrastructure becomes the database for the digital twin city. IoT-sensing facilities and city-level IoT platforms are the tentacles for sensing the city's operating conditions and provide the starting point for remote control of city components. The demand for massive data aggregation and real-time data processing of the digital twin puts increased demand on urban cloud network resources. Network facilities such as 5G networks, narrowband ubiquitous sensing networks and all-optical networks provide channels for complete interconnection; multilevel data storage centres and cloud data centres meet the need for full data storage in the whole domain; advanced computing facilities such as high-performance computing, distributed computing, AI computing, cloud computing and edge computing provide reliable data processing for the digital twin.

INFRASTRUCTURE CASE

Beijing builds an intelligent and advanced 'city brain' to help create a digital twin city[12]

A "1+1+2+N" City Brain has been created in Haidian District, Beijing. "1+1+2+N" refers to one sensory network, one intelligent cloud platform and two centres (a big data centre and an AI computing centre), while N stands for innovative application scenarios. Among them, the AI computing centre is the basic algorithm platform of the City Brain, which provides advanced algorithm and arithmetical support for city management precision, digitalization and intelligence.

Take the field of construction vehicle management, for example. In the initial stage, when the algorithm was immature, the smart recognition had an accuracy rate of less than 60%, easily confusing construction vehicles with postal vehicles and fuel lorries. At present, with the help of an improved AI algorithm, the system processes 1,000,000 pieces of data per day, and the recognition accuracy rate has exceeded 95%. At the same time, the system supervises both the interior and exterior of construction sites, automatically identifying whether a vehicle is permitted or illegal; it has achieved accurate identification, tracking and automatic processing of construction vehicle violations.

Data resources

Full-time and full-volume data resources are the key components of the physical city's digital twin. At present, the construction of digital twin cities promotes not only the convergence of data from government and industry but also the open access to urban spatio-temporal data; this includes the continuous integration of multisource data such as that relating to buildings, bridges, roads, municipalities and other traditional infrastructure, as well as the real-time collection of IoT-sensing data. At the same time, data-collection equipment and capabilities are continuously improved, geographical data is acquired through oblique photography and laser scanning, and 3D data is automatically extracted through AI technologies such as deep learning. All of these measures help form an integrated, highly precise urban digital twin that projects the physical city in all aspects (e.g. above and below ground, indoors and outdoors), which provides data support for the orderly development of the city, and convenient services for citizens.

DATA APPLICATION CASE

Shanghai releases minimum management unit for urban digital governance to create a digital twin system for buildings[13]

In February 2021, Shanghai Huangpu District and Huawei jointly selected the Nanjing Building as a pilot site for the smallest management unit for urban digital governance. Integrating cloud computing, big data, AI, 5G and other advanced technologies, the unit creates a "digital twin system" for the building. The system integrates and accesses multisource data, including: 1) government data such as housing ownership, condition, history and protection requirements; 2) IoT-sensing data such as building vibrations and tilt, smoke sensors, elevators, temperature and humidity, and noise; 3) video AI data – e.g. real-time sensing and early warning of various events such as flow of people, presence of smoke, open windows and fire alarms; and 4) other data such as heat conditions, cleaning and disinfection records, environmental data, subway operation and underground pipe networks. Driven by data, the system delivers digital governance applications such as warning of falling objects, control of flow of people, and facility inspection.

Shanghai has simulated a scene where there is a risk of an object falling from a significant height. When someone opens a window in the building and pokes a smartphone out of the window to take photos, the building's digital twin system detects the hidden danger of falling objects instantly and automatically alerts the security guards in the building through their smart bracelets. Once the security guards have addressed the situation, the smartphone has been withdrawn and the window closed, the digital twin system's "vital sign" is restored to "healthy".

DATA APPLICATION CASE

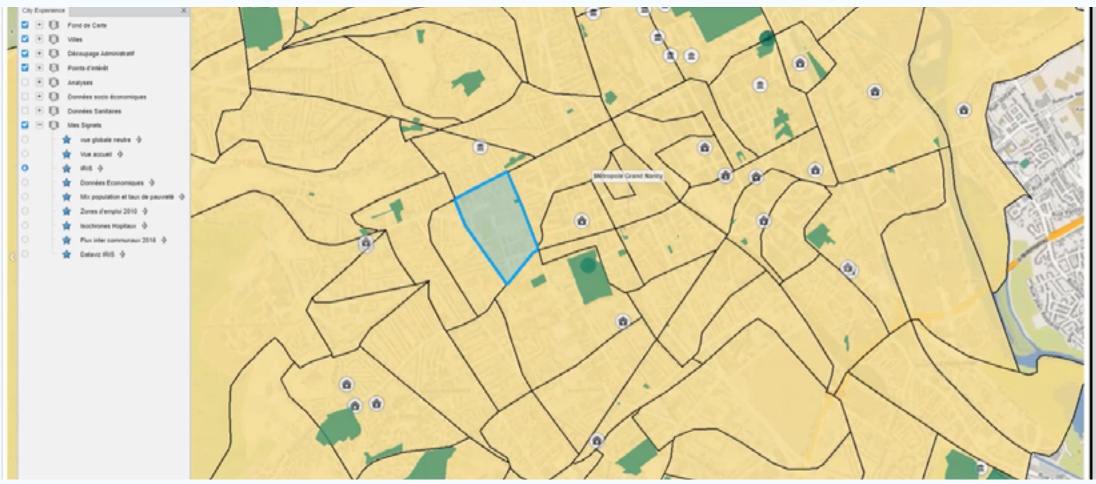
France fuses multidimensional data to build a dashboard for city management during COVID-19 lockdown[14]

The Grand Est region of France has built a dashboard based on a 3D experience platform from Dassault Systèmes. The digital twin technology helps Grand Est find a balance between virus prevention measures and the disadvantages of city lockdown.

The digital twin dashboard helps administrators identify the number of patients that can be accommodated in each region, the number of COVID tests and the change in the number of people testing positive. It can display the number of people living in each region and the status of important public facilities to determine the impact of the lockdown on residents' lives. At the same time, the dashboard can track changes in the number of people hired and those who are unemployed in the region, thus monitoring the impact of the lockdown on the regional economy. All of the information above can be displayed in a panoramic or partial view as needed, helping administrators learn about the pandemic status in a timely manner, and effectively formulate policies regarding the location, length of time and specific measures of the lockdown.

FIGURE 11

Interface of the Dassault Systèmes dashboard

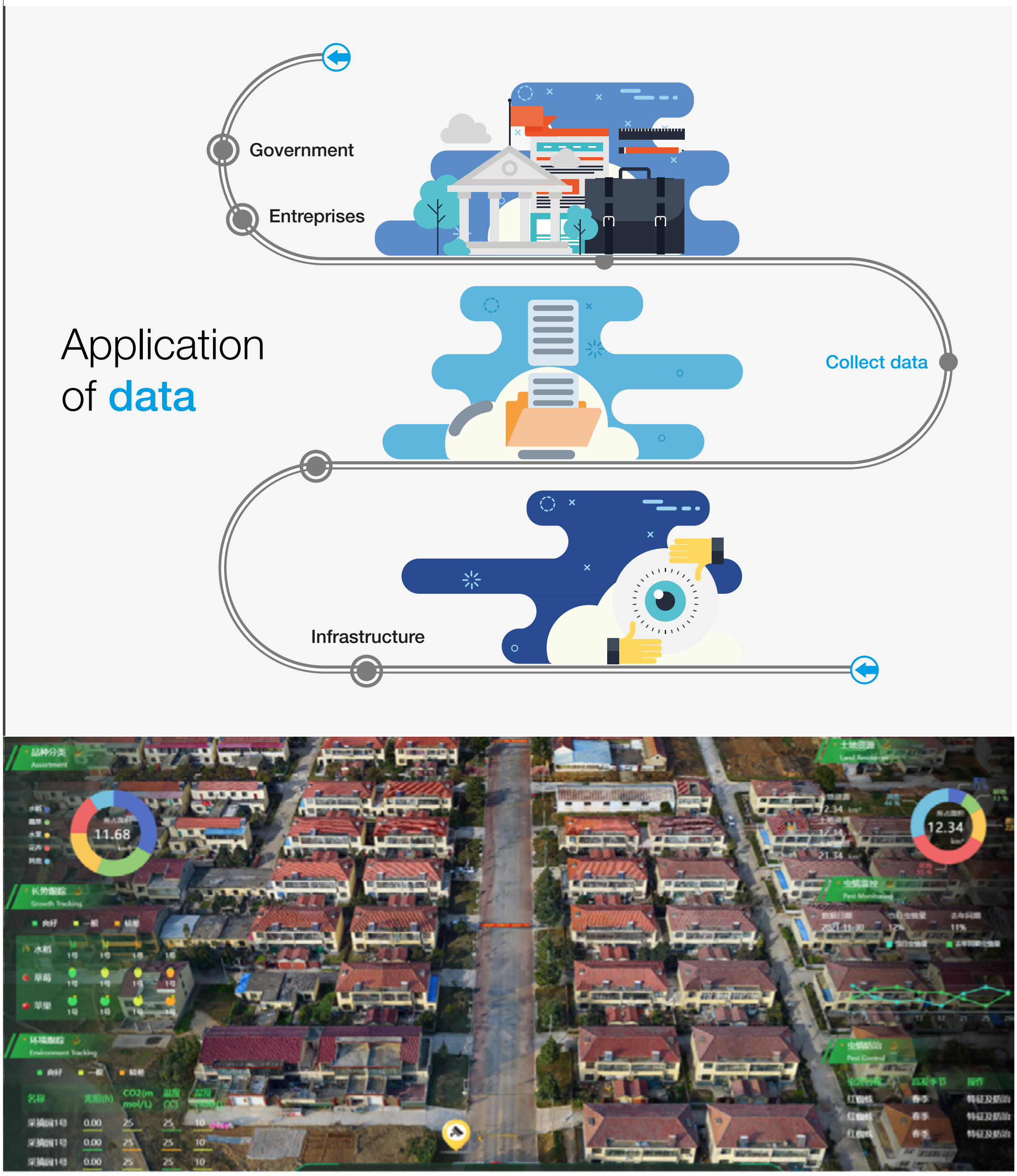


Source: Dassault Systèmes' use case in the Grand Est region of France: https://mp.weixin.qq.com/s/gnlvKpVKRYqL5CT-RtdqMg

Platform capacity

The construction of a digital twin city needs to be supported by a city-level platform that provides a unified dialogue interface, operating system and development environment for the digital twin city. The city-level platform serves as a core hub. Downward, the platform connects various infrastructures and aggregates multisource data about city operation and city components; upward, the platform provides a low-cost, accessible and all-factor platform for the development of different applications, significantly reducing the cost for government and enterprises. At the same time, the platform provides a variety of technical capabilities such as digital twin simulation and spatial computing, providing multidimensional capability support for enterprises to develop digital twin applications and citizens to enjoy virtual-real integration services.

FIGURE 12 **Architecture of digital twin city elements**



Source: World Economic Forum

PLATFORM CONSTRUCTION CASE

Urumqi builds a digital twin platform for a land port, optimizing grouping of cargo to reduce transportation costs

The digital twin of Xinjiang International Land Port provides comprehensive oversight of the port's information in the digital space. Through technologies such as IoT-sensing and spatial computing, the platform incorporates cargo data convergence, automatic matching and optimized grouping, avoiding problems such as excessive reliance on manpower and low efficiency of manual cargo grouping. Scattered goods from various locations are regrouped and placed into corresponding trains bound for different destinations, which significantly reduces transportation costs and opens a fast lane for the export of goods. At the same time, the digital twin helps the park realize smart applications such as container positioning, real-time monitoring of energy consumption, unmanned driving and automatic planning of vehicle paths, all of which help promote the smart upgrade of the land port park.

FIGURE 13

Digital twin port platform

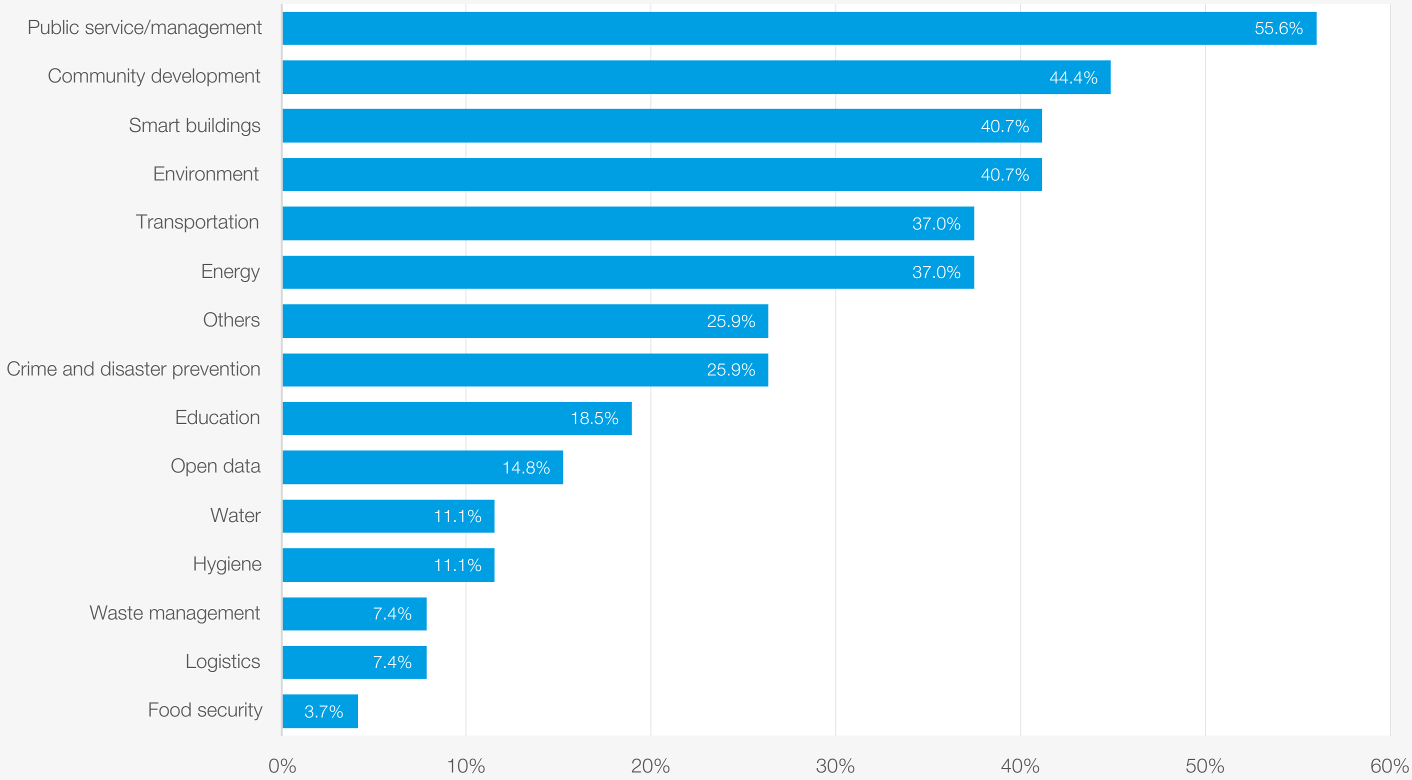
Source: Xinjiang International Land Port (in Chinese): https://mp.weixin.qq.com/s/6WBBqMOJk2YmCxpRq2vl5w

Application scenario

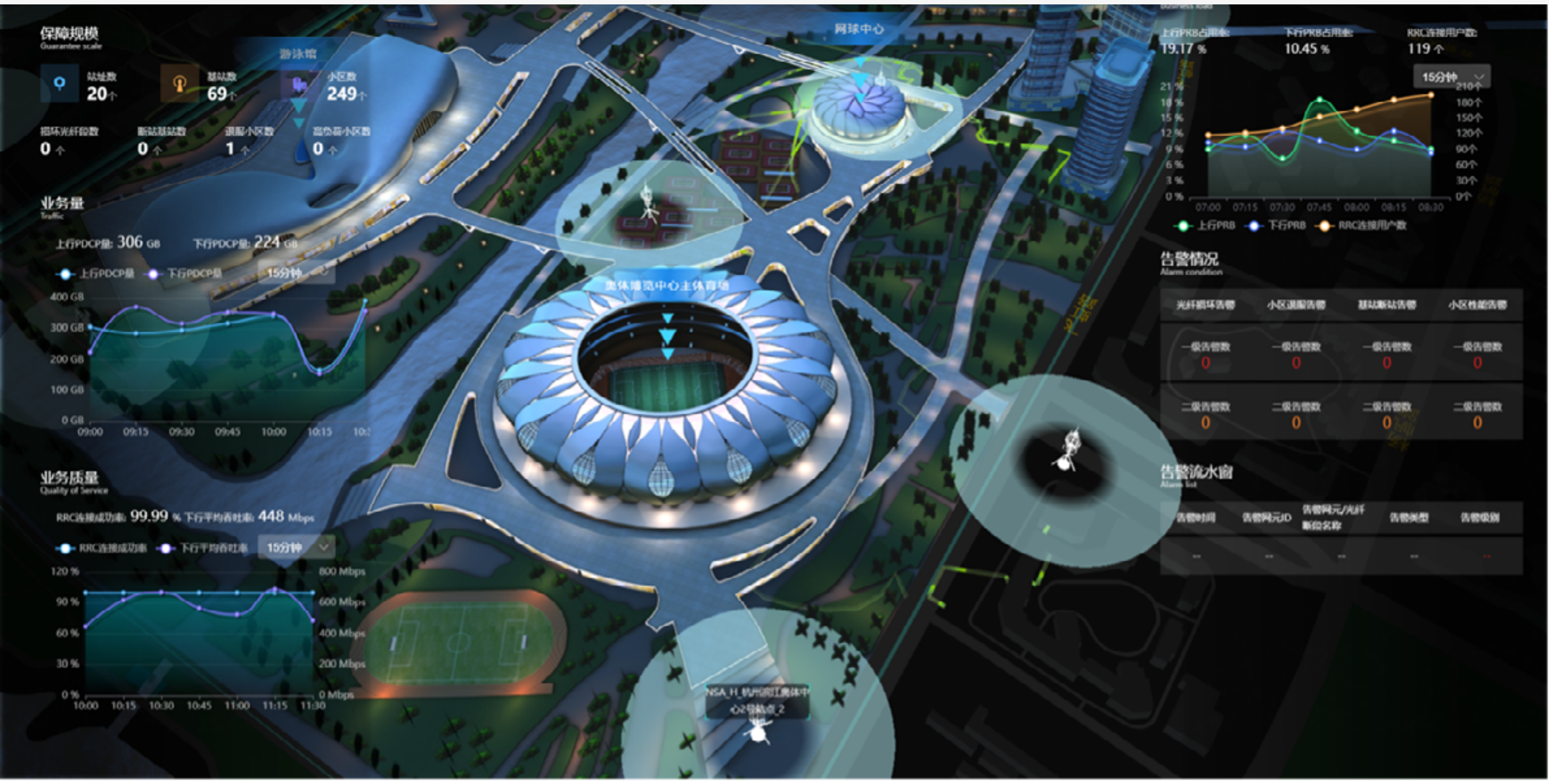
Digital twin city applications have entered into many areas of urban production, life and ecology. Application scenarios bring life to the digital twin city. For example, through digital twins, light and shadow intensity can be simulated. This allows urban lighting to be optimized to achieve the balance between safety requirements and energy-saving targets, which contributes to the low-carbon transformation and liveability of cities. Urban planners can also refine the use, operation and maintenance of energy systems, record the city's carbon trajectory and promote carbon neutrality. At the same time, digital twin technology can help monitor and predict the movement of people, places and objects within the city, enabling comprehensive and systematic advance planning and design, avoiding costly and random demolitions due to problematic construction.

From the cases collected for this report, the top three application scenarios in digital twin city construction are: 1) public services or management; 2) community development; and 3) intelligent buildings, accounting for 55.6%, 44.4% and 40.7% respectively. Of all Chinese digital twin practices, 54% are related to smart transportation and 31% to smart communities. In global terms, more than 40% of practices focus on environmental and low-carbon development. Cities such as Orlando, New York City and Sydney apply digital twin technology to monitor energy consumption and economic returns to help with the low-carbon development of cities.

FIGURE 14 | Percentage of different applications in digital twin city



Source: Declared by relevant enterprises, collated by CAICT



SMART CONSTRUCTION CASE

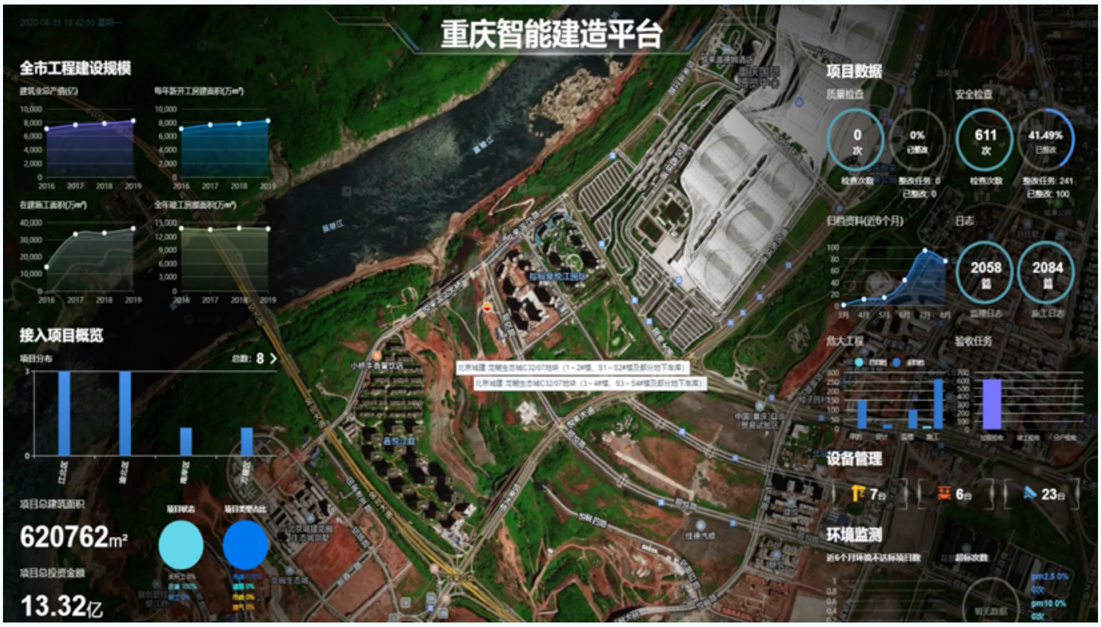
Chongqing uses a digital twin to achieve smart construction, helping industry to reduce costs and increase efficiency

Chongqing has built an internet platform for smart construction industries with the help of digital twin technologies. This platform aims to digitalize the whole process of project management, construction management and government supervision. For government, the platform allows digital control of the engineering process and provides a rationale for leaders' decisions with regards to approval and supervision of projects. For industry, the platform helps create unified standards for engineering and construction data, builds a modular, software-based and reusable industrial internet platform, and provides high-quality application services for SMEs in terms of design, production, construction and labour subcontracting.

At the same time, the Chongqing Housing and Construction Commission encourages enterprises to make use of the platform to carry out pilot digital and smart construction projects through the use of incentive policies, such as advance presales and support for merit-based awards. At present, more than 100 projects have adopted these platform services, which helps to promote the digital upgrade of the construction industry and improve the implementation capacity of smart construction.

FIGURE 15

Chongqing smart construction platform



Source: Tencent

INDUSTRY DEVELOPMENT CASE

Beijing builds a digital twin China International Services Trade Fair to support industry development

With the help of digital twin technology, Beijing has built a digital platform for the China International Services Trade Fair, which serves as the technical basis for the event. The platform provides a comprehensive digitalization and intelligent reconstruction resource for exhibition, forum, negotiation, trade and service scenarios, creates panoramic reproductions of offline physical pavilions and offers online visitors an immersive exhibition experience. It connects online and offline forums with the help of 5G, and breaks down geographical and language barriers through live video broadcasts and intelligent translation. It also builds a cloud-based virtual meeting room that fully fuses the physical and the digital worlds, creating a "service trade fair that never ends". In 2020, the fair attracted a total of 148 countries and regions to participate online, during which more than 20,000 enterprises and 188,000 people registered, more than 5,300 enterprises set up online booths and 550,000 online negotiations were held.

FIGURE 16

Online service trade fair

Source: Beijing JD Shangke Information Technology Co. (in Chinese): https://mp.weixin.qq.com/s/64ypz6jPWUGII254IE-5DA

PEOPLE'S LIVELIHOOD CASE

Tianjin Binhai digital twin processes citizens' requests in 15 minutes

Based on a three-dimensional map of the region, the Tianjin Binhai New Area has built a digital twin platform whereby citizens' needs and requests are collected through different means and presented in real time. The map also presents the entire government response procedure. This platform breaks down the communication barrier between citizens and government and improves the efficiency of government services by logging and responding to people's requests within 15 minutes. Since the start of the COVID-19 pandemic, with the help of the Binhai Hotline and the Hotline for the People, 32,000 cases relating to pandemic reports, resumption of work issues, etc. have been solved. The completion rate was 100%, and the public satisfaction rate reached 94.5%.

FIGURE 17

Tianjin Binhai New Area digital twin platform

Source: Smart Earth

ECO LOW-CARBON CASE

Singapore plans digital twin bike lanes to promote healthy, low-carbon travel for citizens[15]

Singapore is actively promoting cycling as part of its low-carbon strategy and to engage citizens in physical exercise. The authority uses digital twin technology to confirm road conditions through a 3D model, taking into account factors such as road obstacles, tree shading, surrounding facilities, traffic connections and other information, in order to plan bicycle lanes and bicycle parking lots in the digital space. At the same time, relevant departments can assess the safety level of bicycle lanes using the digital twin model to ensure citizens' safety. Government departments have repeatedly promoted the construction of bicycle lanes and related facilities to improve the convenience and safety of cyclists, encourage healthy travel and promote energy saving and carbon reduction in the city.

2.3 External supporting elements of the digital twin city

Strategy and mechanism

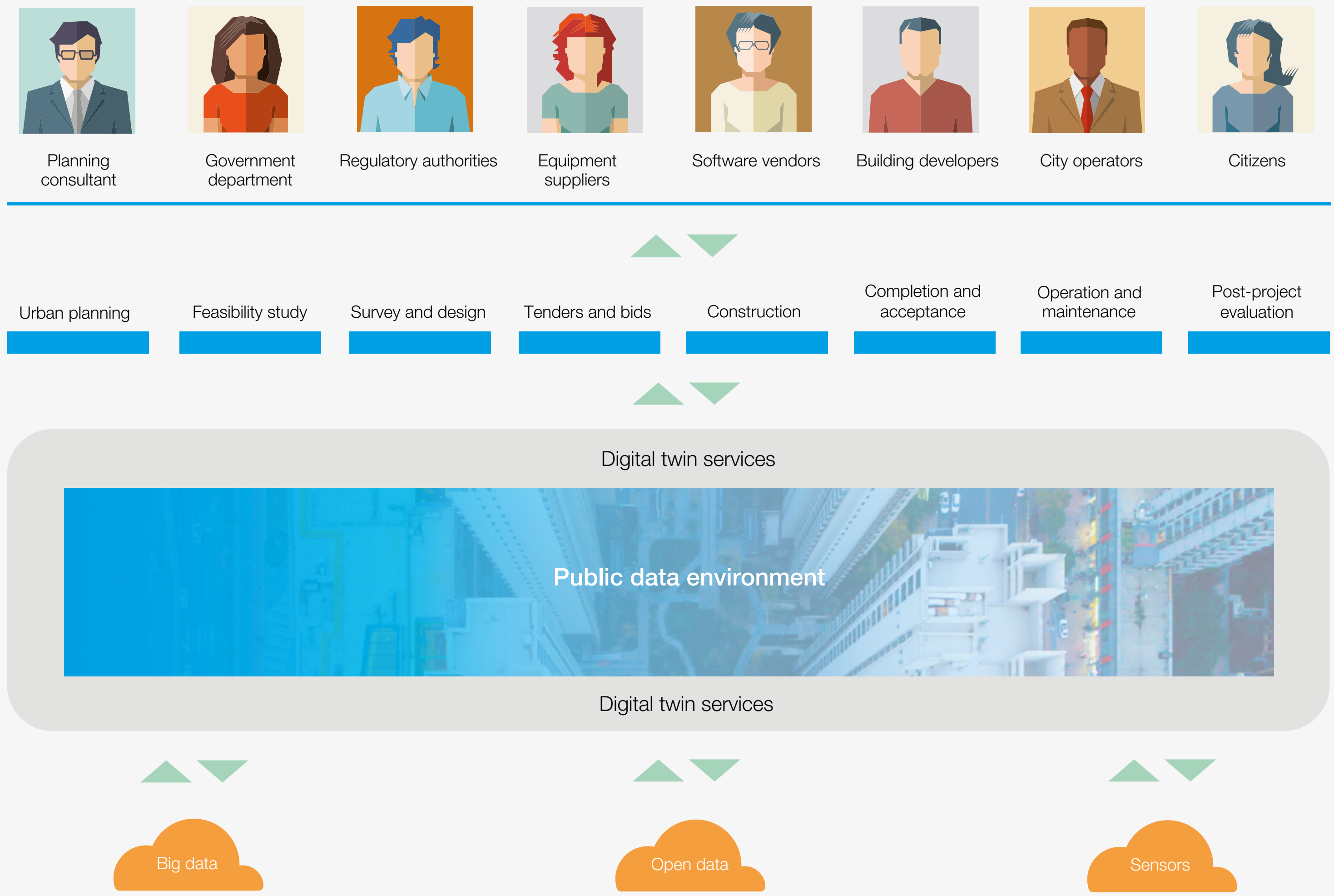
The development of strategies and mechanisms will optimize the policy environment for digital twin cities and promote the standardized, orderly and healthy development of digital twins.

Strategies and mechanisms mainly include: 1) informatization strategies, implementation plans and action plans at different levels, such as national, regional and city levels; 2) encouragement policies, support policies and incentive mechanisms to promote the development of digital twin-related industries; and 3) governance principles and ethical norms to regulate the development of digital twins. As of the end of June 2021, major economies such as China, Germany, the United States and the United Kingdom have issued national policies to promote the research, construction and application of digital twin technology; several provinces and cities such as Shanghai and Zhejiang in China have issued relevant policies to explore the construction of digital twin cities. (See Appendix 2 for details of digital twin-related policies in major economies around the world.)

Stakeholders

Stakeholders are important designers, builders and users of digital twin city technologies and will be an important component of the digital twin city ecosystem. The digital twin city involves many stakeholders such as local governments, ICT (information and communication technology) service providers, citizens, regulators, city operators and property developers. The keys to coordinating and uniting these stakeholders are: a trust mechanism among stakeholders; an alliance ecology of various suppliers; a rich and active citizen participation mechanism; and a city operator mechanism for long-term development.

FIGURE 18 **Stakeholders in the digital twin city**



Source: AEGIS Consulting Group (2020), *Digital Twins: A Sustainable Service Platform*, 2020: https://www.egis-group.com/sites/default/files/documents/publication/2020-broch-num-jumeaunum-en_0_002_4.pdf

> **The development of the digital twin city requires both high-level, long-term consideration of the core objectives, and three-year, five-year and near-medium-term design. Besides, the citizens' level of acceptance and willingness to use the technology should be taken into account.**
>
> Simon Huffeteau, Vice-President, Infrastructure & Cities Strategy, Dassault Systèmes

On the supply side, the government and enterprises should promote the sharing of data and the authorized operation of data through a trust mechanism. Enterprises should be encouraged to establish digital twin industry alliances or communities, and each supplier should build corresponding systems or projects in their own field to their own advantage. On the demand side, more measures should be put in place to encourage and support citizen participation in digital twin city construction and operation. In the future, we should advocate the establishment of citizen participation modules or systems for digital twin city projects to promote projects that are more inclusive, democratic and impactful.

A CASE FOR MULTISTAKEHOLDER COLLABORATION

Virtual Singapore provides a collaborative platform for government, enterprise and the public[16]

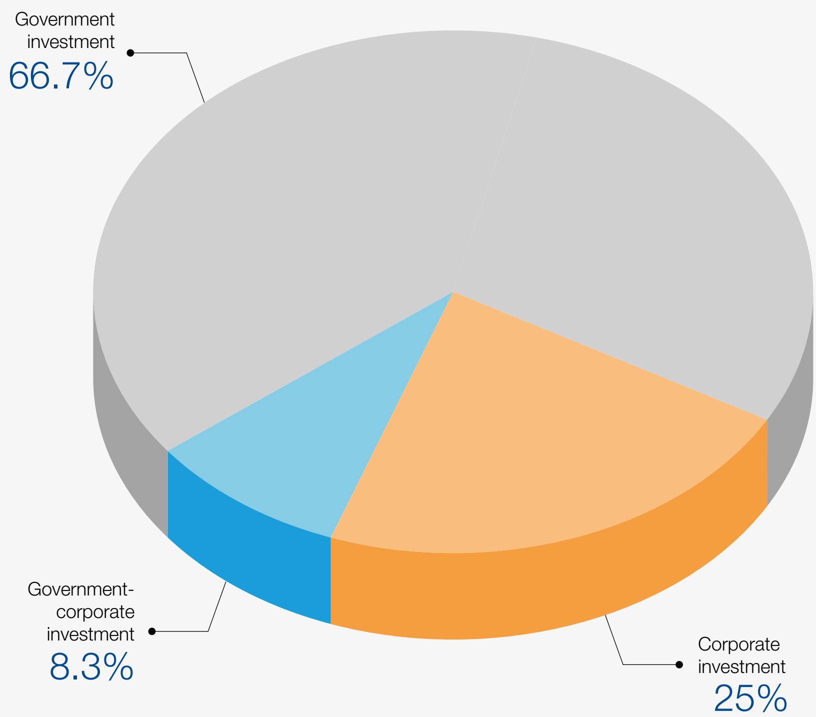
As part of Singapore's Smart Nation initiative, using proper security and privacy-protection measures, Virtual Singapore provides a digital platform for multistakeholder collaboration between the public, businesses, government and research institutions. For the government, the rich amount of data and functions provided by the platform could help with governmental decisions on sensor deployment, upgrading public services and smart nation construction through test running and data analysis. For the public, the Virtual Singapore platform provides access portals, visualization tools, etc., allowing people to view the status of buildings via 3D models, find the best travel routes and give feedback to the government for potential improvements. For enterprises and research institutions, Virtual Singapore provides the necessary access to promote multistakeholder cooperation.

Funding and business model

Funding and business models are the key means of optimizing resource allocation and the construction and operation processes of digital twin city programmes. They also affect the effectiveness of digital twins. At present, the main source of funding for digital twin cities is still government procurement. According to original research, 66.7% of projects are financed and built by the government, with the main operation mode of digital twin city programmes being government-enterprise cooperation, i.e. the government invests and provides public infrastructure, and enterprises build the virtual city. On completion, the government uses the virtual city to make predictions and decisions and serve the people in the region. Only 33.3% of cases are the result of investment by enterprises or jointly built by enterprises and the government.

FIGURE 19

The proportion of funding sources according to original research



Source: Declared by relevant enterprises, collated by CAICT

Currently, Chinese and Singaporean manufacturers are actively promoting the release of digital twin models as cloud services, continuing to tap into value-added services such as human-machine interaction and augmented reality, and promoting the formation of a risk-sharing and benefit-sharing development pattern for digital twin cities. The commercialization of the digital twin city will continue to expand. The digital twin platform can provide a high-precision development environment for property developers, park managers and other enterprises, significantly reducing development costs and shortening the development cycle. At the same time, the digital twin platform provides a digital test space for manufacturers and research institutions in various industries to facilitate simulated operations; with remote and 24/7 access, it is a collaborative platform for multistakeholder construction and sharing.

Digital twins shall be implemented as a "data as a service platform" to rapidly generate a city prototype, automatically build a system space and predict the construction cost of a city in the future.

Saibal D. Chowdhury, Chief Executive Officer, Urbanetic

BUSINESS MODEL CASE

Beijing CBD Park uses digital twin technology to promote the development of a data element model[17]

The management committee of the Beijing Central Business District (CBD) is building a digital twin CBD spatio-temporal information management platform that will create a CBD model data library for lower-cost reuse and data circulation by enterprises within the area, promoting the development of the CBD digital economy and innovation management. At the same time, the CBD management committee has created an incentive mechanism to reward the enterprises whose annual investment in the construction of intelligent management platforms and digital scene applications has reached RMB 2 million ($0.3 million). This mechanism effectively promotes the implementation of digital, networked and intelligent transformations of CBD enterprises using new technologies and helps boost the development of the digital economy.

Standards and evaluation

Standards and evaluation are the regulations followed in the construction of digital twin cities; they are also important references for the evaluation of digital twin city project operations.

In terms of standards, digital twins have received attention from the ISO (International Organization for Standardization); the standardization of digital twin cities in China has officially begun. The National Information Technology Standardization Technical Committee, China's Digital Twin Alliance, the Digital Twin Technology Application Working Committee of the Internet Society of China, the CAICT and other organizations have proposed application scenario-based targets for the standardization of digital twin technologies, taking into account their own business characteristics and digital twin applications. Eighteen research institutes, including Beijing University of Aeronautics and Astronautics and Shandong University, are already conducting research on digital twin standard systems.

TABLE 1 **International standards on digital twin building continue to advance**

Year	Standardization organizations	Efforts
2018	IIC (Industrial Internet Consortium), US	Establishment of the "digital twin interoperability" working group
2019	IEEE (Institute of Electrical and Electronics Engineers)	Establishment of the IEEE P2806 digital characterization standard project
2020	Digital Twin Consortium, US	Establishment of the consortium
2020	IDTA (Industrial Digital Twin Association), Germany	Establishment of the association
2020	ISO/IEC JTC 1/SC 41	Name change of SC41 from Sub-Technical Committee on Internet of Things and Related Technologies to Sub-Technical Committee on Internet of Things and Digital Twins and establishment of ISO/IEC JTC 1/ SC 41/WG6 Working Group
2020	ITU-TSG 7	Establishment of two digital twin standardization projects

Source: Open data, collated by CAICT

In terms of evaluation, there has not yet been a unified acceptance standard and operation evaluation system. The evaluation standards for acceptance, testing, trial runs and operations of each project are not uniform, and users face certain risks and difficulties in judging project completion and construction effects. There is still a need to create an evaluation system for the level of completion, and relevant assessment methods for digital twin city projects in the future.

Cybersecurity

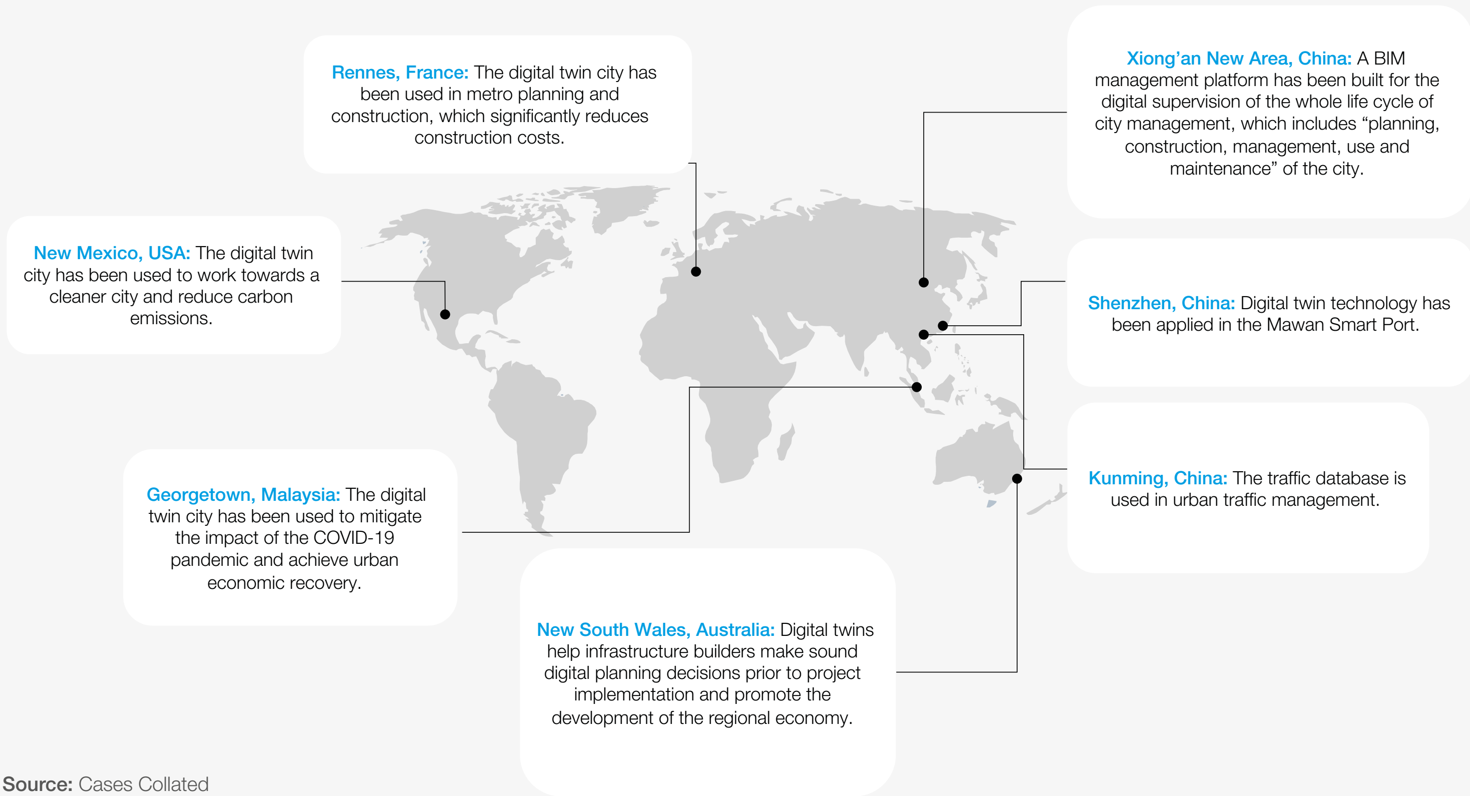
The construction of digital twin cities covers the entire technology ecosystem of cloud computing, internet and device. With data convergence and user scale reaching unprecedented heights, the importance of cybersecurity has become more prominent. In terms of technology application, the digital twin incorporates a number of cutting-edge technologies, such as artificial intelligence, blockchain and IoT, and security maturity is not yet sufficient. With regards to of data aggregation, the digital twin has a wide range of data points and a high degree of concentration, and faces challenges in data security protection and personal privacy protection. During the construction of the digital twin city, it is necessary to adhere to the two-wheel drive of security and development, and the concept of data security should be carried out in all aspects of planning, construction, operation, maintenance and use.[18]

3 Global digital twin city practices

Following an in-depth analysis and evaluation of the collective practices of existing digital twin cities, this report selects seven prime cases by region.

The cases are presented in sections that detail case overview, typical scenarios and case summary. It is hoped that this chapter will contribute to the development of digital twin cities in China and abroad.

FIGURE 20 **Cases of global digital twin cities**



Source: Cases Collated by CAICT

3.1 **Xiong'an New Area, China:** digital supervision of the whole life cycle of the city using the BIM Management Platform

Case overview

The Xiong'an New Area is the first area in China to propose the construction of a digital twin city. According to the "Planning Outline of Xiong'an New Area in Hebei",[19] Xiong'an New Area is required to carry out digital supervision of the whole life cycle of urban planning, construction, management, use, maintenance and repair, and create the "BIM Management Platform for planning and construction of Xiong'an New Area" to achieve the synchronous planning and construction of the digital city and the physical city.

Typical scenarios

The BIM platform of Xiong'an New Area combines six stages: 1) master planning; 2) detailed control planning; 3) scheme design; 4) construction supervision; 5) completion and acceptance; and 6) operation monitoring. Its goal is to increase the efficiency of urban management through the use of digital technologies. Under this framework, planners use the "6 BIMs" of Xiong'an New

Area: BIM0 (status quo); BIM1 (master planning); BIM2 (detailed control planning); BIM3 (design plan); BIM4 (construction supervision); and BIM5 (completion acceptance).

In the BIM3 (design plan) stage, the platform provides consultation and review services that enable users to make multilevel and multidimensional comparisons of the spatial layout, building height, architectural style and related design parameters of different design plans. At the same time, combined with the requirements of the relevant planning controls, the platform can digitalize various types of control elements, to allow the automatic review of various design parameters.

FIGURE 21 **Digital twin city helps users make multidimensional comparison between different design schemes**

Source: 51WORLD

In the BIM4 (construction supervision) stage, the BIM platform takes an innovative approach to incorporate construction site management into the platform supervision on the basis of construction model auditing and filing. Before the project starts, the construction unit must submit a 3D field library model of the construction site to the administrative authority in accordance with unified standard requirements. In addition, connecting the platform with the intelligent supervision system governing engineering construction in Xiong'an New Area allows interoperability and sharing of data about the construction site, e.g. information about people, machines, materials, methods and the environment.

Case summary

The Xiong'an New Area's BIM management platform for planning and construction of Xiong'an New Area, combined with data collected through sensing devices or the IoT, allows for real-time monitoring, early-warning and condition assessments of the city. This reshapes urban planning and construction procedures and effectively simplifies management and approval processes.

3.2 **Kunming, China:** building a digital twin traffic database to improve comprehensive traffic management

Case overview

Kunming is the capital city of Yunnan Province, China, and one of the most important cities in western China. In order to ease traffic congestion at rush hour and improve the city's traffic health index, Kunming built a digital twin-based urban traffic database to enable urban traffic managers to observe and control the city's traffic operations.

Typical scenarios

Three-dimensional digital restoration of urban road scenes. The Kunming Intelligent Transportation Project uses digital twin technology to achieve a 1:1 digital recreation of roads, vehicles, traffic facilities and geomorphic environmental elements, etc. As a result, data on, for example, the network of roads, the vehicles driving on those roads and the state of the equipment (e.g. traffic lights), is projected into the three-dimensional digital world in real time with a high degree of accuracy and precision.

FIGURE 22 **The digital restoration of traffic elements**

Source: Aliyun: www.aliyun.com

Panoramic monitoring of urban traffic. Combining data from radar, video, the internet and the road network, the platform achieves an accurate quantitative evaluation of urban road operations at the macro, meso and micro levels. Macroscopically, it provides an overview of Kunming city, showing, for example, the congestion delay index and regional traffic speed; mesoscopically, it offers an accurate display of vehicle movement through digitalization of vehicles and by fully recreating the vehicle trajectories; microscopically, it shows the efficiency of traffic flow at intersections, with lane-level indicators such as queue length, flow rate, speed and delay; it also indicates the road safety situation by capturing any road emergencies or traffic violations.

Case summary

Comparative analysis shows that traffic management in Kunming has been substantially improved by the platform, with average delays decreasing by more than 10% throughout the day. Traffic in the peak evening hours has been optimized to the greatest extent, with average delays decreasing by 20% within the first ring of Kunming's ringroad network, by 10% on arterial routes and by an average of 12% at single intersections (with the highest being 20%).[20]

3.3 **Shenzhen, China:** Mawan Smart Port – using digital twin technologies to achieve smart port operation and navigation management

Case overview

Located in China's Yangtze River Delta, Mawan Smart Port, established on 30 September 1986, provides a model case of how to upgrade a traditional bulk cargo terminal and transform it into an automated terminal. The port uses digital twin technology to create a 1:1 realistic recreation of static port scenes and a data-driven simulation of dynamic port operations, offering such functions as all-round real-time dynamic recreations of port operations, flexible switching of equipment operation perspectives, visualization of trailer operation paths, search and positioning of equipment and containers, 3D spatial management of yard and container services, and statistical analysis of operational efficiency.

Typical scenarios

Data-driven generation of more than 100,000 digital containers. By accessing the container data in the container service management system, Mawan Smart Port dynamically generates containers in the digital twin 3D version with the same location, appearance, number and type as their physical counterparts, which allows users to direct the storage of containers and quickly locate them. This function also helps users to select eligible containers with specific dimensions, thus improving the efficiency of yard and container service management.

Real-time data driving operations in a 3D environment. Mawan Smart Port can access historical operation data to create a historical operation review and help find the causes of operation anomalies and thus offer solutions. As a result, a knowledge base is created to help subsequent onsite scheduling as well as the formulation and optimization of operational plans. It is also possible to access real-time operational data, enabling real-time operational monitoring, which overcomes the shortcomings of video monitoring and improves real-time operational scheduling efficiency. In addition, it is possible to access operational plan data so that the plans can be verified and optimized.

FIGURE 23 Realistic recreation of a static port scene

Source: 51WORLD: www.51aes.com/

Case summary

With the help of digital twins, artificial intelligence, 5G applications, the BeiDou Navigation Satellite System, automation, smart ports, blockchain and other technologies, the load distribution efficiency of Mawan Smart Port is 15–20 times higher than that achieved using manual methods, and comprehensive operational efficiency is increased by 30%. Efficient management of operations and movements with the smart port are achieved.[21]

3.4 **Georgetown, Malaysia:** projecting the potential impacts of new urban projects through digital twin city models

Case overview

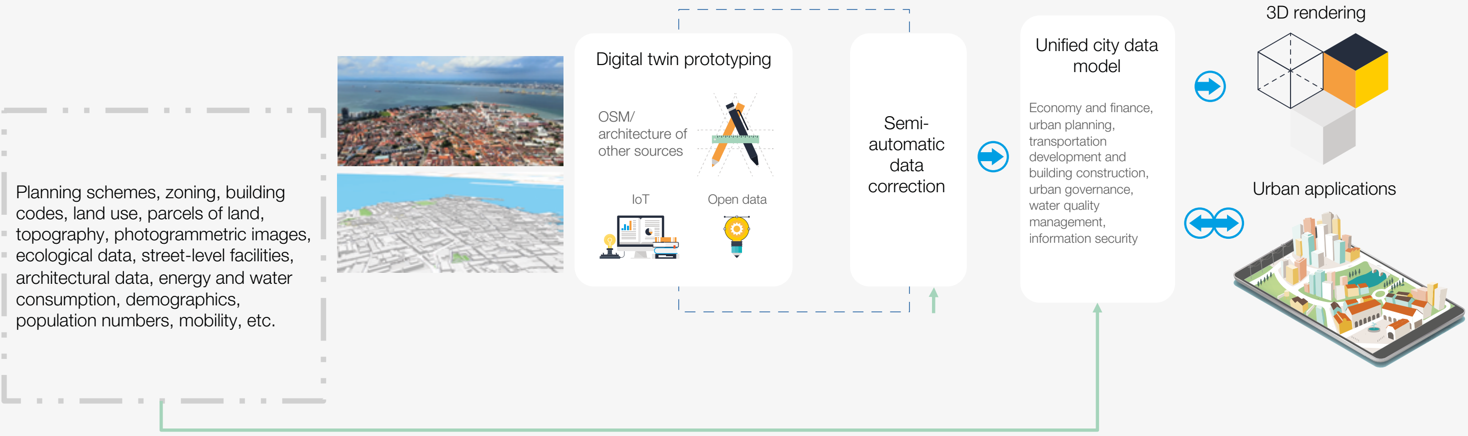
Tourism is the second largest source of revenue in Georgetown, the capital of Penang, Malaysia, but the city's tourism industry has been severely affected by the COVID-19 pandemic. To drive economic recovery, Georgetown is using a digital twin city platform to assess the feasibility of new projects, infrastructure capacity needs and sustainability, aiding in the reallocation of land use and helping to attract investment.

Typical scenarios

Predicting the impact of various risks on urban infrastructure and improving urban resilience. By creating an urban data platform, Georgetown is able to collect and aggregate large and diverse sets of data from public and private domains, including planning schemes, ecological statistics, information on street facilities, energy and water consumption, and building and population data. Continuous monitoring and visualization of public properties such as roads and bridges through integrated sensor data assists in city maintenance, threat monitoring (both natural or man-made threats such as fire, earthquakes, surface temperature increases and flooding), and prediction of the impact of multiple types and levels of risk to the city.

Simulating and extrapolating the potential impacts of new urban projects to improve urban liveability. The digital twin platform can be used to analyse, simulate and visualize the relationship between regional planning scenarios and economic, social and environmental outcomes. This information can then be used to assess the feasibility of new urban projects. In addition, the platform enables city stakeholders to predict and solve problems such as potential hazards, congestion, urban overheating, waste emissions and unemployment. Furthermore, it can provide interactive services for local residents, such as immersive shopping experiences, to improve urban liveability.

FIGURE 24 **Process of urban simulation and extrapolation**



Source: Digital Twin City Project of Urbanetic, collected by CAICT

Case summary

Digital twin technology helps Georgetown to: 1) revisit its land use plans and urban sustainability regulations; 2) anticipate and analyse urban risks, with a view to reducing the harm caused by them and helping the city to move rapidly beyond them in the future; 3) achieve lower infrastructure costs, increase municipal revenues and attract investment; 4) improve liveability, resilience and environmental sustainability.

3.5 **New Mexico, USA:** creating clean cities based on the digital twin city platform to effectively reduce carbon emissions

Case overview

New Mexico is located in the southwest of the United States, covering an area of about 314,900 square kilometres. It is the fifth largest state in the United States, with a population of about 2,097,000 (2019 estimate).[22] In 2019, the state passed the Energy Transition Act (ETA), which proposes that the state shall become a clean energy leader and achieve 100% clean energy by 2050. Founded in 2009, Cityzenith, a US software company, proposes to transform cities through digital twin technology to make them cleaner and healthier, and contribute to the "Clean Cities – Clean Future" vision. As a result, the State of New Mexico has partnered with Cityzenith to develop SmartWorldPro, a digital twin city platform, to help build new "smart infrastructure" and achieve carbon neutrality goals.

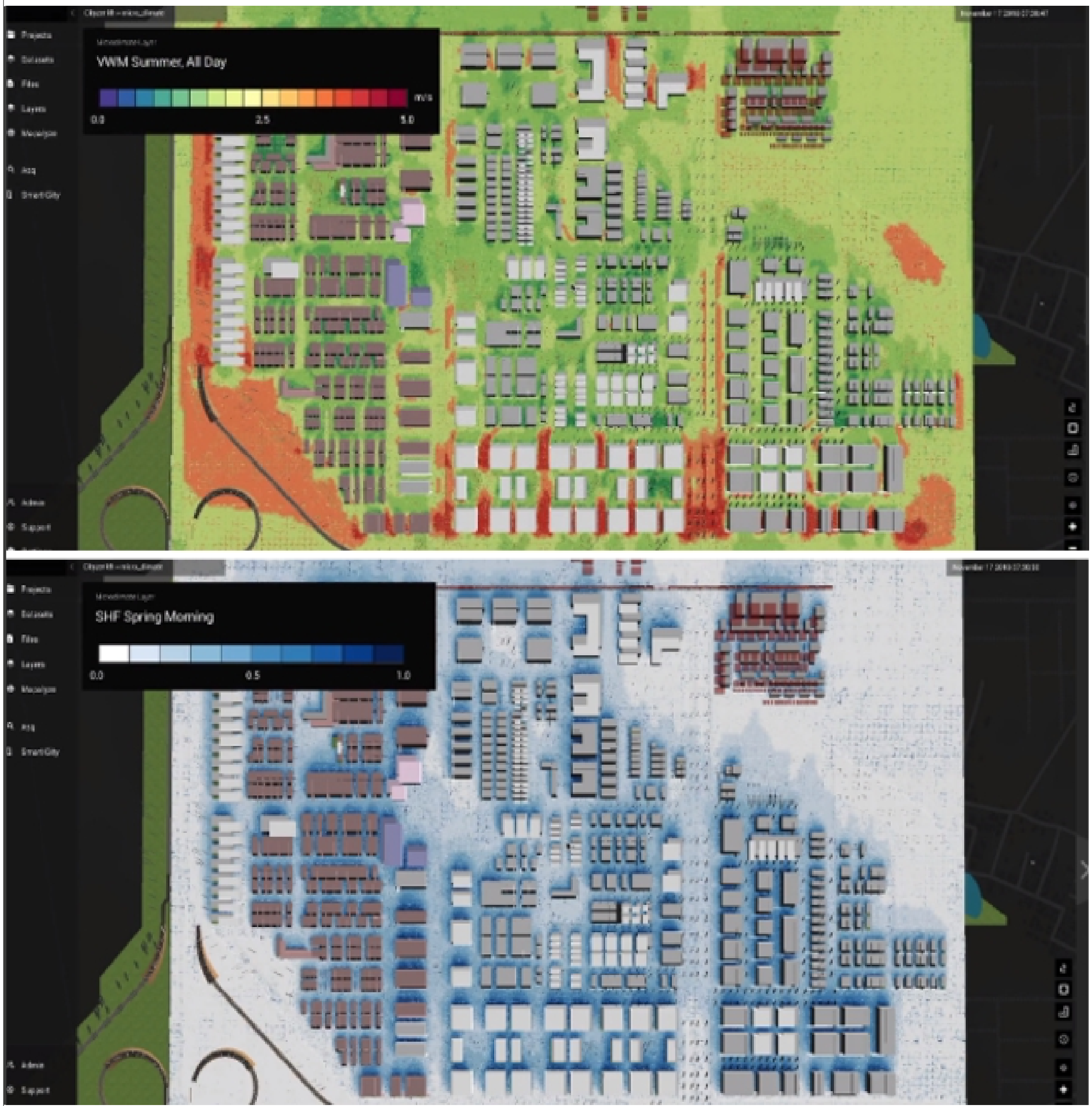
Typical scenarios

Providing full life-cycle services for buildings. Cityzenith's digital twin city platform, SmartWorldPro, is a tool for building planning, management and operations. The platform is used by architects, contractors and asset managers to carry out site selection, planning, design, construction, operation, maintenance and sales.

Solving problems in data integration and providing template tools for rapid expansion. To overcome the difficulty of integrating data from different sources such as BIM, GIS and IoT, SmartWorldPro has significantly expanded and upgraded its data import and integration capabilities, providing the ability to import hundreds of data types into a common dashboard. Using 3D templates, users can quickly scale from a single building to a portfolio of hundreds or even thousands of buildings, including information on rooms, floors, textures and major equipment. At the same time, users can customize rendered scenes to their liking, with visualization tools such as colour palettes, preset objects and base maps.

Build a platform and professional community. SmartWorldPro has built Mapalyze, an application store for building professionals, as a library of analysis tools. Mapalyze provides users with AI-based analysis such as solar analysis, viewpoint analysis, sociological analysis, traffic studies and climate impact simulations. In addition, SmartWorldPro offers a variety of deployment methods, including customized solutions, software as a service (SaaS) and software development kits (SDKs).

FIGURE 25 | **Analysis of the effect of temperature in different seasons**



Source: Cityzenith: https://cityzenith.com/

Case summary

Cityzenith is already reducing carbon emissions, maximizing savings and improving efficiency with its digital twin platform in cities such as New York City, Pittsburgh and Phoenix. In Albuquerque, New Mexico's largest city, Cityzenith conducts modelling and works to create smart, connected communities for cities, large venues and even entire states. As a digital twin platform for city infrastructure, in the future, it could reduce city operating costs by 35%, increase productivity by 20% and reduce carbon emissions by 50–100%.[23]

3.6 **Rennes, France:** Virtual Rennes helps to significantly reduce costs in metro planning and construction

Case overview

Rennes is the second largest city in northwest France and an important tourist destination. Metropolis Rennes and Dassault Systèmes are working together to create a virtual Rennes, a digital model of the city to be used for urban planning, decision-making and management and as a service to citizens. The 3D platform built by Metropolis Rennes and Dassault Systèmes is a collaborative environment that enables stakeholders to collaborate and communicate in designing innovative projects, products and services.

Typical scenarios

During the planning and construction of the metro passenger railway in the Maurepas district of Rennes, digital twin technology was used to collect and merge, share and analyse city-scale data to develop a 3D model of the metro through a design and simulation approach. The model can show both more macroscopic information such as the topography of the land around the metro station, as well as more detailed information such as rooftop solar panels, emergency evacuation routes and shaded pathways. At the same time, it is able to simulate the impact of metro construction on traffic signals, foot traffic in bus stations, commuting times and changes in community architecture.

Case summary

Virtual Rennes can optimize the decision-making process. Through 3D models and simulation technology, Virtual Rennes can show the evolution of different programmes for decision-makers in a graphical and extremely easy-to-understand way, which helps urban planning departments transform experience-driven decisions into data-driven decisions. Based on digital twin technology, it can reduce the construction time of metro stations by 70%, completing three months earlier. Besides this, it can help create multi-governance systems, establish stakeholder communication channels, enable the participation of urban designers and the public, and strengthen communication and cooperation between government, citizens and other stakeholders at the early stage of the project. In this way, public consensus on the effectiveness of the digital twin can be built.

3.7 **New South Wales, Australia:** developing a digital twin proof-of-concept model to support multistakeholder participation in urban planning

Case overview

The New South Wales (NSW) Government, in partnership with the Data61 department of the Commonwealth Scientific and Industrial Research Organisation (CSIRO),[24] has developed the digital twin proof-of-concept model: a complete, real-time, accurate and reliable 4D framework model that projects a physical environment that can enable real-time spatial-based data sharing and collaboration to help policy planners and project developers better design and manage the future of cities.

Typical scenarios

Aggregating data from multiple sources for wide-scale modelling. The digital twin platform is the largest 3D modelling project in Australia's history. It uses sensor-equipped fixed-wing platforms to capture images of large areas with high accuracy, with the end result expected to cover 3,392 square kilometres and include a 3D grid map of Sydney's western region captured at less than 6cm pixel resolution. The platform extensively aggregates data from multiple sources; visualizes historical data from government, industry and communities; and models buildings and natural resources above and below ground using data obtained from water, energy and telecom utilities.

It serves as a basic platform to support various applications. The digital twin platform integrates digital engineering assets, building information models and real-time application programming interfaces (APIs) for managing assets, public transport, air quality and energy production. For example, using the digital twin platform and blockchain technology, NSW puts information on building design approval, data verification and construction management on the blockchain, which provides the basis for subsequent smart asset management. In addition, NSW has developed a minimum viable product and upgraded it from a two-dimensional space to a four-dimensional visualization platform[25] that allows developers to use digital twin technology to create digital models of cities and communities.

Data services are available to the public. The digital twin platform is integrated with the NSW Spatial Collaboration Portal to provide real-time information and a data service centre allowing people to search, find and share spatial information. Through the integration of the platform and the portal, digital services are created based on user needs, enabling user-centric, accessible and convenient government services. It also enhances public engagement capabilities and promotes the NSW Government as a global model for service and digital innovation.

Case summary

NSW's spatial digital twin project can now produce an online Western Sydney map of 22 million trees with height and canopy attributes, more than 540,000 buildings, nearly 20,000 kilometres of 3D roads and 7,000 3D strata plans, which can effectively help infrastructure builders to plan soundly and digitally before projects are implemented and to facilitate regional economic activity.

> The digital twin still faces significant challenges, and China is still in the early stages of exploration. Existing challenges include poor coordination among government departments, the fact that technology is still in development, lack of standardization of platform models, the need to readapt the city's organizational structure and management system, and data security and privacy protection risks.
>
> Wu Hequan, Academician, Chinese Academy of Engineering

4

Challenges and recommendations for the digital twin city

Cities face huge challenges in meeting the housing, infrastructure, transport and energy needs of their urban populations, and urgently require new ideas and solutions.

4.1 Challenges for the digital twin city

1. The challenge of scientific understanding and value perception

Industry and society lack an objective and rational understanding of the digital twin city, and its possibilities are still being actively explored from diverse perspectives. Digital twin city technology is still undergoing rapid development and change. Relying on a single technical perspective risks forming a one-sided understanding. For example, paying too much attention to 3D modelling of cities and the visualization of city components, while overlooking the equally or even more important simulation extrapolation and virtual-real interaction capability available through digital twin technologies, could lead to an unbalanced development of the technology.

Relying on visual modelling technology and ignoring the ultimate value of simulation and reality optimization. The development of digital twin city technology is being determined not only by supply but also by demand. In promoting the construction of digital twin cities, some cities focus too much on the fine reproduction of city details through high-precision technology, while lacking an in-depth analysis of the application requirements and goals. This could result in a disconnect in business cycles such as urban planning, construction, management and services, causing digital twin technology to be reduced to a flashy but useless ornament. In the short term, the realistic presentation of city images has certain practical significance in terms of city branding and reputation, but in the medium and long term, as the technology evolves and investment continues to increase, this cognitive model cannot tap into the core value of digital twin cities in terms of their spatio-temporal control and fine management.

2. The challenge of data governance and privacy issues

The limited data-collection ability of urban IoT-sensing can cause insufficient application depth. Uneven data-collection capability, inability to effectively sense underlying key data, inconsistent multidimensional and multiscale data collection and uneven construction of IoT and other sensing facilities may lead digital twin cities to become ex ante models, simulation demonstrations and virtual simulations. However, there would not be enough depth in the application of real-time dynamic sensing and city-scale twin interaction to take advantage of the technology's full potential.

Lack of standardized governance of varied urban multisource data. At present, with digital twin cities still in the development period, there is no unified standard system. In practice, the development of the digital twin city relies on solutions from various developers and has poor system interoperability. There is no unified consensus on its technical architecture or data accession standards, which makes the integration, fusion and unified processing of varied data more difficult, leading to drawbacks such as low data quality and insufficient governance effectiveness.

Centralized processing of huge amounts of data leads to an increased risk of data security failures and privacy leakage. The data sources are extensive, and data storage and processing are highly concentrated in centralized institutions such as city intelligence hubs, which may lead to paralysis in city operations in the face of cyberattacks. In addition, video data and trajectory analysis involves the use of citizens' private data, which can easily lead to personal privacy abuse if the data cannot be effectively anonymized or placed under strict control by qualified authorities.

3. The challenge of resource and business sustainability: insufficient interdisciplinary human resources

To accurately and completely understand the digital twin city, and recognize and excavate its practical path and development potential, integrating experts and teams from multiple specialities – such as urban management, demand analysis, digital technology and algorithm modelling – is a matter of urgency. These experts need to work through scientific and theoretical issues and jointly explore the patterns of twin virtual-real interaction. At present, the digital twin city is mainly dominated by IT, mapping and other professional practitioners; there is a significant need for interdisciplinary talent in algorithm modelling and business analysis.

There is a lack of industry algorithm modelling resources within the city. The digital twin city involves multidimensional and multi-industry systems, and there is an urgent need for professional knowledge bases and industry models in various aspects of data, models and interaction. At present, except for relatively mature model libraries in the fields of transport and construction, many urban governance areas lack interoperable knowledge bases and industry simulation models, which can hinder the development of the digital twin.

The digital twin business model relies too much on government. The high research costs of digital twin cities is difficult to translate into practical application benefits, so the government has become a major source of funding for the development of digital twin technologies. While waiting for the digital twin technology system to be brought to maturity, there is an urgent need to attract the participation of a wider range of citizens, institutions and other market players, innovate the digital twin city business model and form a risk-sharing and benefit-sharing development pattern.

4.2 Suggestions for government

1. Both top-down and bottom-up measures are needed to stimulate innovation

Strategic directions need to be defined and policies formulated that keep pace with the times to promote the sustainable development of digital twin cities. Municipal authorities and planning agencies should take into account the city's resource endowment, industrial characteristics, cultural and religious backgrounds, geographic environment and other comprehensive factors when formulating a digital twin city strategy and implementation plan. The appropriate entry point and breakthrough areas should be identified and thoroughly explored. At the same time, it is recommended that local governments set up an intelligent city operation centre (IOC) to connect data resources scattered around various city management units, based on big data and system integration. The centre would play multiple roles such as situation monitoring, emergency control, display and reporting, process management and auxiliary decision-making, and would serve as a decision centre, early-warning centre, governance centre, command centre and display centre for city management, with full-time external management and internal horizontal coordination. In addition, a unified digital twin base for the city should be constructed by attracting data contributions from commercial organizations and the online market through a government-business-academia cooperation model. The construction of the digital base should also be guided by a hierarchical classification management system for data assets as well as relevant laws and regulations.

2. The application scenario should be human-centric

The construction of the digital twin city should be application-oriented, people-oriented and demand-driven. Cities should not invest in constructing a digital twin city for its own sake. Instead, the government should analyse the demand for monitoring urban operational indicators and develop cross-sectoral and cross-industrial scenarios that exploit the benefits of digital twin technology. Examples would include: airspace modelling above and below ground (pipeline networks, energy facility planning and construction, etc.); danger analysis of scenarios with high human risk (mines, forest fires, etc.); complex simulation and exercise scenarios involving multiple subjects (firefighting, port dispatching, emergency responses to large events, etc.) and multilayer life scenarios (e.g. citizens can apply for customized services such as shopping, education and medical services on a single digital interface). In conclusion, a "technology-only" mentality needs to be developed: only if the tools cater to the needs of the population can a people-friendly and human-centred urban digital service system be built.

Furthermore, private organizations should be encouraged to provide digital twin solutions and service products, which would then be applied in urban planning and construction management as they are developed.

3. Guarantee data quality and security

A hierarchical data system for the digital twin city needs to be put in place to ensure a balance between data value and personal privacy. The government should pay attention to data ownership and key data protections, and gradually establish a graded and classified data resource system and supervision mechanism for data with different levels of precision and confidentiality. At the same time, depending on the level of priority (e.g. emergency response), data security and privacy-protection strategies should be formulated and a security governance framework covering the whole life cycle of data should be established. As a result, a friendly, safe and welcoming technology ecosystem can be built.

4. Innovation should be boost through the joint participation of interdisciplinary expertise

A multidisciplinary team for collaboration and innovation should be created. Based on existing digital twin city project teams, urban planners, private technology companies, algorithm designers from universities, citizens and others could be invited to participate in the joint construction and sharing of digital twin technologies. Moreover, by holding regular digital twin city seminars and training sessions, experts from industry, academia and research institutes can jointly participate, explore and analyse the inner workings of urban development, publicize and promote digital twin city concepts and industry practices, and help city managers improve the efficiency and effectiveness of their practices. At the same time, there should be a focus on improving the digital literacy of citizens and the general public and attracting public participation in the construction and sharing of digital twin cities.

4.3 Recommendations for industry

1. Lower the technical threshold

The threshold for building digital twin city scenes should be lowered to attract more practitioners and key stakeholders. At present, there is a defined threshold for non-GIS and BIM practitioners to engage in 3D modelling and visualization. To solve this problem, the construction of public service platforms for digital twins by government departments is required. There is also a need for an industry alliance to promote digital twin open source software, as well as low code and zero code,[26] to develop some SaaS micro-applications or open the necessary API-enabled interfaces for inexperienced developers. Examples of these applications include online prototype drawing and model customization services. The lowering of participation threshold could help city managers, operators, product managers and even city residents work together to enrich digital twin city scenarios and improve existing business processes.

2. Engage in strength-driven innovation

Unique advantages need to be established in the digital twin field, avoiding indiscriminate development and thus forming a prosperous innovation ecosystem. As TED founder Chris Anderson suggests: “Bring enough people with a common interest together and they will start to share and compete and improve. The bigger the crowd, the greater the chance of innovation, and the more people who witness and benefit from that innovation.”[27] This is also true for digital twin cities, which have a wide range of dimensions that cannot be captured by only a few companies. There are many key technologies and industrial elements involved in the digital twin, such as IoT perception, all-factor modelling and expression, visualization and presentation capabilities, data fusion, spatial analysis and calculation, simulation and deduction, virtual-real integration and interaction, self-learning and self-optimization, etc. From these technologies, each organization should cultivate its independent strengths, complement and integrate them, break the mindset of industry competition, establish incremental business models based on open interconnections and open up new business spaces to form new business models.

3. Refine industrial standards

There should be a focus on standard-led industrial implementation, forming interconnected and mutually beneficial standardization partnerships. Standardization should play a fundamental role in promoting digital twin cities, refining common requirements and normative standards from the practices of the United States, China, Singapore and other regions advanced in the use of digital twin cities: for instance, carry out cooperation on digital twin city reference architecture, city information models (CIM) and twin city maturity; strengthen the exchange and technical cooperation of standardization personnel from ITU and ISO; establish an open and unified framework of municipal digital service platforms; improve the interoperability of related systems; promote the information interconnection and data sharing of digital twin cities on a larger scale; and promote the formation of mutually beneficial and win-win international standardization partnerships.

4. Innovate business models

Government and enterprises should collaborate in business model innovation to expand the “to C” market, and transform from a one-time project relationship to a long-term operation partnership. First of all, the digital twin city cloud service market should be actively developed, providing an on-demand supply and customized designs for digital twin SaaS services by establishing interoperable, safe and relevant cloud services. Furthermore, depending on the different levels of precision of the twin city model, the service can be extended from “to G” and reach “to B” and “to C” services. For example, the finer the level of detail (LoD), the higher the level of sensitive material of the model, which is suitable for government-led precision mapping, pipeline network planning and other fields; a rougher LoD model, on the other hand, can be opened to industry and development companies in an orderly manner, allowing them to develop their own components or tools on the 3D model, forming the foundation of the digital metaverse.

The digital twin city is the perfect combination of ICT technology and human civilization. In the future, a scientific decision-making system combining “spatio-temporal big data + artificial intelligence” will build a green system with less pollution, less waste and sustainability; holographic communication and intelligent control will create a digital and physical space that “knows you better”; the miniaturization and popularization of sensors will make the “calculable health” of city residents a reality, resulting in residents being healthier and having a better quality of life. Blockchain, digital watermarking, privacy enhancement and other technologies will build a more solid foundation for the sustainable development of digital twin cities. The digital twin city has set an evolutionary direction for cities and become the future of cities. Through the joint efforts of multiple stakeholders, future cities will not only become a physical space for human survival and development, but also a digital spiritual home for human beings to embrace.

In 2022–2023, CICT and the World Economic Forum will continue to promote the integration and innovation of industry, academia, research and application, jointly publish annual reports and construction guidelines for global digital twin cities, establish a library of consummate cases and toolboxes, hold high-end forums, promote exchanges and cooperation among governments, enterprises and academia, carry out city pilot projects and help global digital twin cities develop in a people-oriented and sustainable manner.

Appendices

Appendix 1

Global research perspectives on digital twin elements

Company or institution	Perspectives
Siemens AG, Germany	The Digital Twin Application Model contains three major elements – Digital Twin Products, Digital Twin Production and Digital Twin Performance – that form a complete solution system encompassing existing Siemens products and systems, such as Teamcenter and PLM.[28]
Dassault Systèmes, France	Emphasis is placed on consistency of experience, consistency of principles, a single data source and macro-micro unification between the digital twin and the physical entity.[29]
Ansell Asia Pacific, US	Digital twins incorporate several elements such as numerical simulation tools, model downscaling techniques, auxiliary modelling languages and digital twin platforms.
AEGIS Consulting Group, France	A successful digital twin city should have five major elements: 1) clear goals; 2) open data management in line with international standards; 3) trust-building mechanisms; 4) support for changing city management; and 5) a trusted digital twin operator.[30]
Deloitte	The six elements driving the development of the digital twin are: 1) simulation technology; 2) new data sources; 3) interoperability; 4) instrumentation; 5) visualization; and 6) platforms.[31]
PwC	The digital twin system includes infrastructure, connectivity networks, platforms, applications, data standards and management, security and privacy, and other key elements.[32]
CAICT	The digital twin city covers various technical categories such as new mapping, geographic information, simulation, intelligent control and deep learning, and presents nine core capabilities:[33] 1) IoT perception and manipulation; 2) digital representation of all elements; 3) visualization; 4) data fusion and supply; 5) spatial analysis and calculation; 6) simulation and deduction; 7) virtual-real interaction; 8) self-learning and self-optimization; and 9) crowdsourced extension capabilities.[34]
Beijing University of Aeronautics and Astronautics	Tao Fei proposed the five-dimensional model of the digital twin, which consists of five elements: 1) physical entities; 2) virtual entities; 3) twin data; 4) services; and 5) connections.[35]
Tsinghua University	TSG According to Du Mingfang, the three elements of the digital twin city are: 1) data; 2) models; and 3) services.[36]

Source: Open data, collated by CAICT

Appendix 2
Policies related to digital twins in major global economies

Country	Date	Policy	Summary
China	March 2021	Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and Vision 2035 of the People‘s Republic of China	Improve the city information model platform and operation management service platform, build the city data resource system and promote the construction of a central resource for city data. Explore the construction of digital twin cities.
US	February 2020	Digital Twins for Industrial Applications: Definition, Business Values, Design Aspects, Standards and Use Cases	From the perspective of the industrial internet, this explains the definition of the digital twin, its business value, its architecture and the necessary foundations for its creation, and describes the relationship between the industrial internet and the digital twin through practical application cases in different industries.
UK	April 2020	The Gemini Principles	Construct values, standards, principles and roadmaps for national-level digital twins in order to unify standards for the development of digital twins across independent industries, enable efficient and secure data sharing among twins, unlock the value of data resource integration, and optimize social, economic and environmental development methods.
Singapore	2015	Smart Nation 2025	The Smart Nation and Digital Government Working Group, led directly by the Prime Minister‘s Office, clarifies national development priorities and establishes a national-level working group (SNDGO) to coordinate the implementation of Smart Nation 2025. Virtual Singapore, developed by NRF (National Research Foundation) in collaboration with Dassault Systèmes, contains static and real-time data to address issues such as urban energy consumption, waste disposal, community navigation, transport planning and disease transmission.

Source: Open data, collated by CAICT

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23. Cityzenith: https://cityzenith.com/.
24. Commonwealth Scientific and Industrial Research Organisation (CSIRO): https://www.csiro.au/. This is the largest national research organization in Australia. Its primary role is to provide new scientific avenues for the Australian Federal Government through scientific research and development.
25. In the four-dimensional visualization platform, the dimension of time is added on top of the three-dimensional space to show historical, present and future construction.
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