Technology Report

City information modelling and urban digital twins

Executive summary

The development and delivery of smart cities involves many different systems, types of data, and sets of information. This complexity, and the dynamic interaction between the large numbers of stakeholders and city systems, makes planning and managing cities a great challenge. Without a tangible operational model to combine cross-sector data and information, the holistic, cross-boundary planning of cities, districts and neighbourhoods remains constrained. Therefore, new and effective tools are needed to enable the delivery of better city services and to make the urban environment more liveable, inclusive, safe, resilient and sustainable.

City information modelling (CIM) and urban digital twins (UDT) are two emerging technologies for smart cities that aim to provide such tools. Both offer solutions for data processing, urban analysis, design, simulation and modelling. They connect all involved stakeholders and actors to collaboratively deliver the vision of a smart city: a sustainable, inclusive, healthy, prosperous and participative city. They provide solutions for smart cities based on open standards and a multiscale and multitemporal database that integrates a wide variety of data sources presenting the full range of smart urban features, systems and processes.

CIM and UDT are similar but different technologies. So, what are the overlaps and differences between CIM and UDT? This report examines the theories, concepts, technologies and standards of both CIM and UDT to attempt an answer to that question. It also includes case studies of both CIM and UDT to help illustrate how these are being used in practice.

The report is based on a virtual forum held on 22-23 June 2021. The forum was hosted by the IEC (International Electrotechnical Commission) and organized jointly by the IEC Systems Committee Smart Cities and by Subcommittee 41: Internet of things and digital twin, of Joint Technical Committee 1 operated collaboratively by IEC and ISO. The virtual forum included both presentations and interactive discussion sessions, and this report covers the content of both, along with some brief reflections of the organizing committee.

Specifically:

- Section 1 introduces the background and aims of the report.
- Section 2 investigates the concepts, definitions, and theories of CIM and UDT.
- Section 3 examines the state of the art of the technologies and practices of CIM and UDT.
- Section 4 includes three case studies of CIM and UDT located in different countries/areas. Specifically, these relate to the developing CIM platform in Nanjing, China and the New South Wales Spatial Digital Twin and Greater Hobart Region Digital Twin in Australia.
- Section 5 indicates the existing standards work relevant to CIM and UDT as well as what other standards work is needed. The content covers the standards roadmap, a digital twin reference architecture, an open digital twin framework for smart city ecosystem, and a scoping out of CIM standards requirements via use case collection and analysis.
- Section 6 is an overall discussion of the differences and overlaps between CIM and UDT based on presentations and discussion in the forum.

- Section 7 concludes the report with a summary of what has been learned, the gaps between the current state of affairs and what is needed going forward, and recommendations for what types of standards and other work are needed to support the development of CIM and UDT in the future.

Acknowledgments

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List of abbreviations

Technical and scientific terms

AEC	architectural, engineering and construction (technologies)
AI	artificial intelligence
API	application programme interface
AR	augmented reality
BIM	building information modelling
CAD	computer-aided design
CIM	city information modelling
CityGML	City Geographical Markup Language
DCDCE	data collection and device control entity
DT	digital twin
DTRE	digital twin representation entity
DTUE	digital twin user entity
FAIR	findable, accessible, interoperable and reusable
FE	functional element
FSDF	Foundation Spatial Data Framework
GeoSciML	Geoscience Markup Language
GIS	geographic information system
ICT	information and communication technologies
IE	information exchange
IFC	Industry Foundation Classes
IoA	Internet of Automation
IoT	Internet of Things
IT	information technology
LAN	local area network
LGA	local government authority
MDS	mobility data standard
MUDDI	Model for Underground Data Definition and Integration
NGO	non-governmental organization

O&M	operation and maintenance
PME	physical manufacturing element
PSS	planning support system
R&D	research and development
SDI	spatial data infrastructure
SDO	standards developing organization
SDSS	spatial decision support system
SRD	systems reference deliverable
UCM	urban construction management
UDT	urban digital twin(s)
UPS	uninterruptible power supply
VR	virtual reality
WLAN	wireless local area network
XML	Extensible Markup Language
2D	two-dimensional
3D	three-dimensional
4D	four-dimensional

Programmes, organizations, institutions and companies

ANZLIC	Australia and New Zealand Land Information Council
BSI	British Standards Institution
CDBB	Centre for Digital Built Britain
CEN	The European Committee for Standardization
GHDT	Greater Hobart Digital Twin
IEEE	Institute of Electrical and Electronics Engineers
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
NIC	National Infrastructure Commission
NSW	New South Wales
OGC	Open Geospatial Consortium

Glossary

city information modelling
CIM

practice of using interactive digital technologies in the process of urban planning and city management by all actors and stakeholders, to collaboratively deliver the vision of a smart city: a sustainable, inclusive, healthy, prosperous, and participative city

[Source: Jorge Gil]

alternatively:

development of digital representations of a city made up of large quantities of geo-located data, often including real time data, which enable better city planning and management

[Source: IEC SRD 63273 ED1 CD]

digital twin
DT

digital representation of physical (and sometimes social) assets for verisimilitude, simulation and prediction

alternatively:

digital representation of a particular physical entity or a process with data connections that (1) enables convergence between the physical and digital states at an appropriate rate of synchronization, (2) has the capabilities of connection, integration, analysis, simulation, visualization and optimization, and (3) provides an integrated view throughout the life cycle of the physical entity or the process

[Source: ISO/IEC WD 30173]

urban digital twin
UDT

digital twin at the urban scale deployed to enable transformation of how cities are planned, built and managed in order to deliver better services to make the urban environment more liveable, inclusive, safe, resilient and sustainable

Section 1
Introduction

City information modelling (CIM) and urban digital twins (UDT) are two sets of technology-enabled practices used to help city planners develop smart cities and city officials and business leaders to manage them. They are needed because the complexity of city planning and management, and the necessity to address sustainability, mean that an extensive use of data and scientific knowledge is required to help design resilient, safe and liveable cities.

CIM is the practice of using interactive digital technologies as part of the process of urban planning. The concept emerged as an evolution of building information modelling (BIM) which uses technology to generate digital representations of buildings and civil engineering works. It involves the collection, analysis and visualization of data to help planners, designers and construction managers make informed decisions. BIM also leads to an increased digitalization of urban design and the planning process.

A digital twin is a collection of disparate information made available within a computer-generated digital representation of sophisticated and complex physical assets and of the processes and human environment in which those assets function. It is capable of providing historical, near-real-time and future interactive spatial views of multiple datasets simultaneously, as a basis of superior decision-making. UDT combine 3D city models with dynamic data gathered using sensors and geospatial technologies to help us better understand our cities. They are based on the concept of verisimilitude to develop a static structure with dynamic properties. The origins of the technology are to be found in manufacturing.

Aims of the report:

a) Gain a better understanding of the state of the art of the theory, technology, practice and standards of CIM and UDT

b) Identify the similarities and differences between CIM and UDT

c) Identify the requirements for standards needed for CIM and UDT

d) Promote the exchange of information and experiences and enhance the conversation between CIM and UDT experts and practitioners

Scope of the report:

a) Theories and concepts of CIM and UDT

b) State of the art of the technologies and practices of CIM and UDT

c) Case studies of CIM and UDT

d) Existing standards and standard gaps of CIM and UDT

e) Differences and overlaps between CIM and UDT

Section 2

Concepts, definitions and theories of city information modelling and urban digital twins

2.1 Concepts, definitions, and theories of city information modelling

The concept of CIM quietly emerged more than a decade ago as a natural evolution of BIM to address larger city-wide challenges. A first reference can be found in an AECbytes article from 2005 by Lachmi Khemlani. Since then, CIM has been adopted by the software industry and in urban design and planning research and practice circles. This tacit acceptance of the term suggests that CIM represents a useful or even necessary concept, providing a focal point to the various actors involved in digital urban design and planning, and in the production of supporting digital technologies. One can also find references to urban information modelling or models, but in this context, they are considered to be identical concepts.

Why is CIM suddenly important? Planning and designing cities presents a huge challenge due to

- the complexity of, and dynamic interaction between, the various stakeholders and various systems that make up the urban world;
- the sustainability goals that contemporary society has set out to (urgently) meet, which are spelled out in the UN Sustainable Development Goals and the UN-Habitat's New Urban Agenda.

Therefore, urban planners look for support from data and evidence to support the development of smart cities. To achieve this vision, information must be collected, analyzed, and visualized on the physical, ecological, material resource, social, transportation and other urban systems, to enable citizens and professionals to make informed decisions in this area.

This path involves the increased digitalization of urban design and planning processes, as a necessary transformation for supporting informed, transparent, collaborative, decision-making and design. CIM is an emerging concept to frame such practice.

But there is also a need to understand and define this concept, so that CIM can be developped more effectively. A review of academic literature on CIM [1][1] was undertaken to determine a definition and develop a conceptual framework of CIM. There are obviously multiple perspectives on CIM in the literature, depending on the field of research and practice where the work originates. CIM can be seen variously as: a concept based on BIM and computer-aided design (CAD), in which the city model results from the sum of its (physical) parts, mostly different types of buildings; a 3D model with extended and enriched geoinformation for representation and analysis of the city and its systems; or an enabling platform to go beyond simple representations of the city to support planning of the smart city.

1 Numbers in square brackets refer to the bibliography at the end of this report.

All these perspectives combined contribute to the identification of the various components that constitute CIM, which are summarized in the conceptual framework presented in Figure 2-1 and in a concise definition of CIM:

"City information modelling is the practice of using interactive digital technologies in the process of urban planning, by all actors and stakeholders, to collaboratively deliver the vision of a smart city: a sustainable, inclusive, healthy, prosperous and participative city". "CIM consists of an ecosystem of interoperable (open source) tools from different knowledge domains, for data processing, urban analysis, design, modelling, simulation and visualization. These tools are connected via shared ontologies to a semantically-rich integrated urban model, based on open standards, in a multiscale and multitemporal database that integrates a wide range of (big) open data sources representing the full range of urban features, systems and processes" [2].

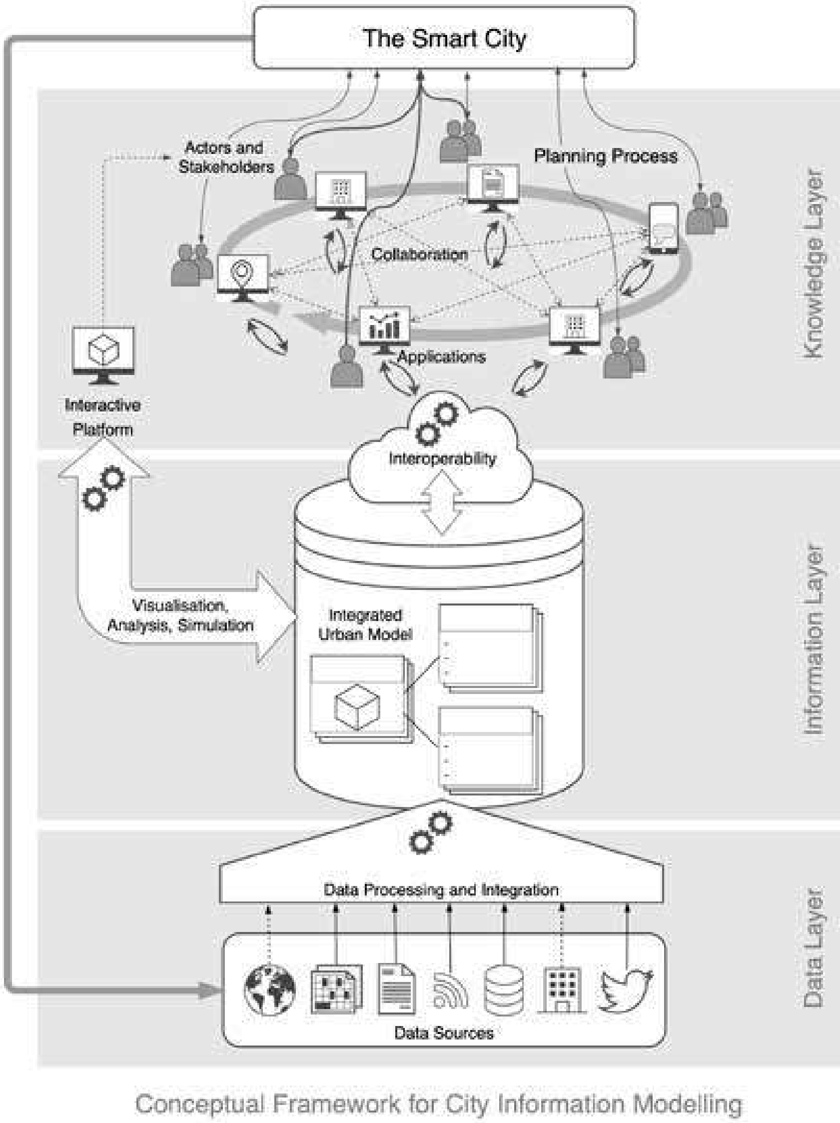

Figure 2-1 | Conceptual framework of CIM representing its various components and their relations [1]

CIM constitutes more than the tools and data involved. It is a practice of using technology in an interoperable and interactive way to make decisions and plan for smart cities. Communication and collaboration between all stakeholders, planners and decision-makers around the table, perhaps using different systems and different software, is fundamental in order to achieve the goal.

Obviously, technology plays an important role, and the disciplines related to smart cities and digital urban design and planning (e.g. digital twins, BIM, big data, geographic information systems (GIS), planning support systems (PSS)) can be mapped in relation to the CIM conceptual framework to understand how these technologies contribute to the different components and layers of CIM (see Figure 2-2).

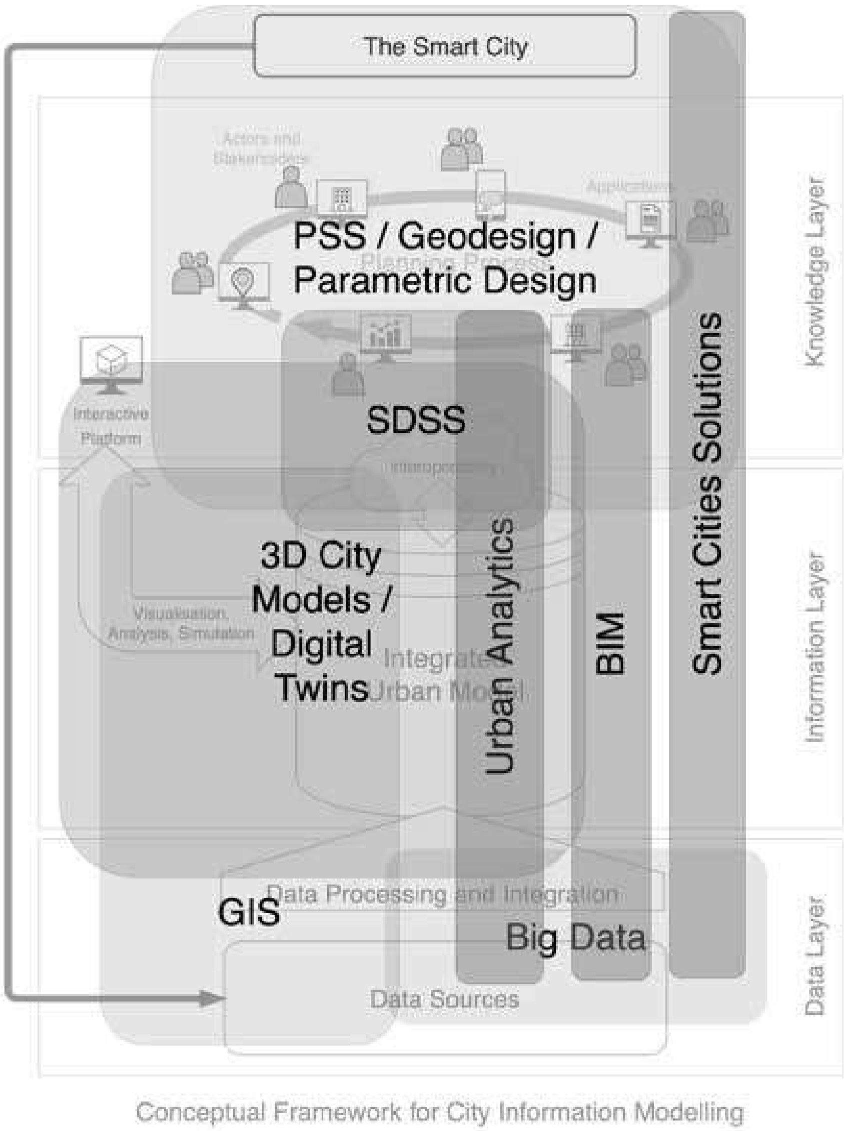

Figure 2-2 | Mapping of disciplines and technologies that support the realization of CIM [1]

While technological and scientific innovation are fundamental to enable the digital transformation towards the smart city, it must not be forgotten that this can only be realized through the involvement of smart citizens and smart planners and designers. As Cedric Price famously stated in 1966, “Technology is the answer, but what was the question?”

Many challenges and questions remain for the future development of the CIM concept:

- User focus: usability and usefulness of applications for stakeholders. How can CIM support different planning and design processes, actors and stakeholders?
- Integration/interoperability: linking data, models, standards-based applications, ontologies, databases. How can different disciplines align, and technologies be linked in CIM?
- Openness: open data, open standards, open source. How can CIM leverage the potential of diverse and new data sources to provide insights on the multitude of physical, social, and economic layers that make up a city?
- Regulation: new business models, security, and privacy. In what ways will CIM engage urban design and decision support with artificial intelligence (AI)?
- How can CIM transform the way urban design and planning is taught?

2.2 Concepts, definitions, and theories of urban digital twins

In covering the concept of UDT, this subsection will consider the underlying critical notions and origins of this concept and then review the outcomes of a recent event focussing on the potential of this framework, the *Location Powers: Urban Digital Twins* virtual summit, held 12-14 January 2021 and organized by the Open Geospatial Consortium (OGC).

2.2.1 Digital twin concept

The digital twin concept has its origins in mechanical engineering and the use of finite element models to be able to digitally represent a component or a machine while fulfilling the conceptual requirement of verisimilitude. In other words, not only does the model look the same in terms of visualization, but it also behaves the same as the component or machine represented. In this way, changes to the digital twin of the device, or seeing what happens when the digital twin runs, can enable predictions or simulations of how the real device will behave. But at the same time, the model is not the same as the object. It is a digital representation and therefore safer. If you change the wrong parameter, the programme blows up, but the turbine itself doesn't explode.

What is important is that it has these two aspects: the model framework is both spatially and temporarily accurate and has dynamic properties that enable it to deal with the things that change for a system during operation, as well as with changes that occur because of the effect of the system’s environment. Due to this verisimilitude, the digital twin can be used not only for visualization but also for interaction. It can in some way behave in the same manner as the real object and enable simulation and prediction of what would happen to the physical asset based on the digital behaviour.

This sort of digital representation has been extended or brought over to modelling at urban scales and urban environments. It is a very promising concept but, even with the tremendous computing capacity now available, it faces the limits of scale complexity and the ability to sense what is going on in that larger more complex environment so as to represent it properly.

2.2.1.1 Digital twins at urban scale

In terms of digital twins at urban scale, the goal is really to transform how cities are planned, built and managed in order to deliver better services to make the urban environment more liveable, inclusive, safe, resilient and sustainable. The mechanism must be responsive and interactive in order to provide insight that then enables people to improve how the city works or even to be connected directly to control devices, such as in the operation of a water system.

Now, because UDT are based on geospatial and temporal information, technology frameworks, city models, data science, sensor webs, crowd-sensing, digital exhaust, etc., multiple models may need to be used, including functional or physics-based models and heuristic models, so that the goals and targets above can be achieved.

2.2.1.2 Multiple themes for urban digital twins

One way to deal with the scale and complexity of UDT is to specialize thematically and thereby reduce the scope of each twin. For example, digital twins have been developed for water provision, as well as mobility, energy and other urban themes. Of course, these aspects of the built environment are not really independent of each other. If these thematic twins are based on the same representation of the (3D) physical fabric of the city, the same spatio-temporal basis, then they will be able to coordinate, or even be harmonized. They can constitute steps toward building a true system of systems or at least be coordinated together as needed.

It is still difficult, even at a thematic scale, to be sure that UDT will provide accurate predictions, because cities are emergent phenomena. A twin which appears to be an accurate static representation is not necessarily able to support predictions of its future state. Linkages between twins is one way at least to detect when changes to one system may induce changes in another (see Figure 2-3).

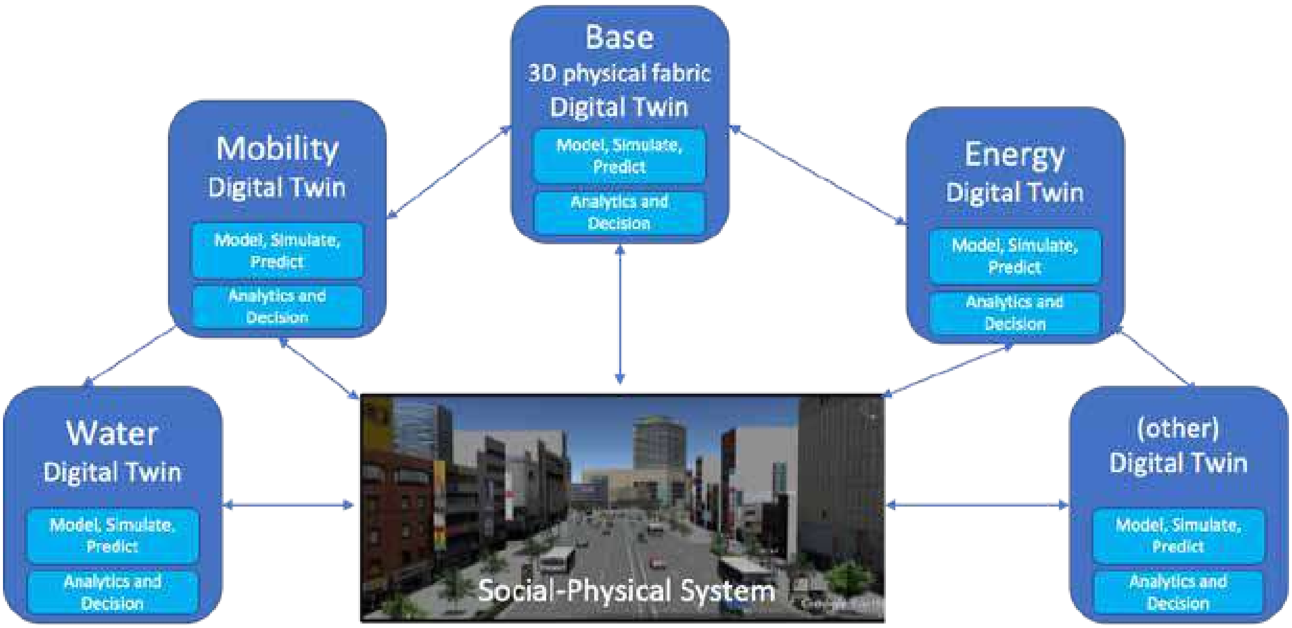

Figure 2-3 | Social-physical system

2.2.1.3 Urban digital triplet

While UDT constitute a powerful and forward-looking concept, they may actually be inadequate for providing a complete perspective on human settlements. This is because the twin construction is focused on providing a digital dimension that corresponds to the physical dimension of the city. Cities, however, are not just composed of buildings and civil works. They are also composed of people and their interactions, both with each other and with physical space as represented in the places that constitute human perspectives of inhabited space. The social dimension needs digital representation as well.

Another challenge is that an accurate, detailed, and up-to-date spatial data framework is needed to form the basis of a successful urban digital twin or triplet. Several problems need to be solved in developing such a framework, including spatial matching between different scales, datasets and data formats. Time needs to be represented, as well, to reflect the way in which the city changes over time, including its properties and geometric structures. There is also the question of ownership and usage and sharing rights. A representative and current digital twin needs to access and incorporate a wide variety of data (see Figure 2-4).

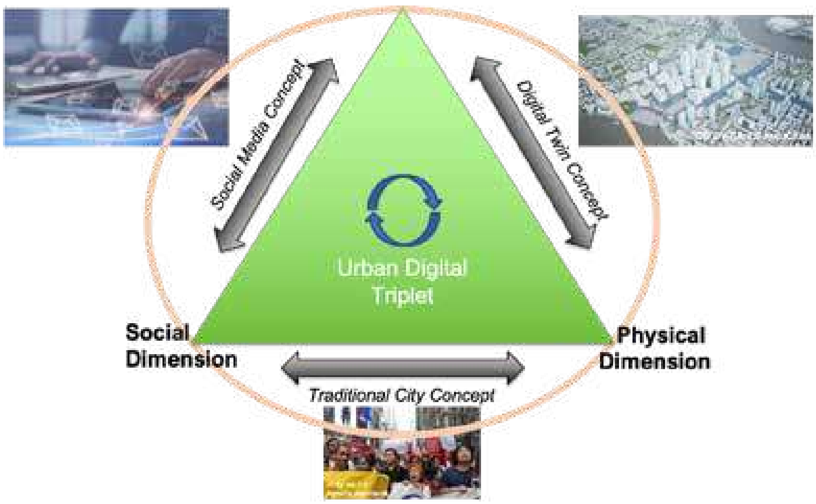

Figure 2-4 | Urban digital triplet

2.2.1.4 Digital twins as convergence

The digital twin/triplet concept really shines when it reinforces the importance of convergence between different perspectives of the city and its life. Spatial data infrastructures may form the backbone or framework, but urban models do not currently flesh out all the interactions that bring a city to life. The challenge posed to urban digital models, whether twins or triplets, is to sense and adapt to the inhabitants (SensorWeb/Internet of Things (IoT)) so as to provide services that make a city more liveable and sustainable. All four perspectives – spatial, model, sensing and services, need to work together in all three domains: digital, physical and social, for this to be possible (see Figure 2-5).

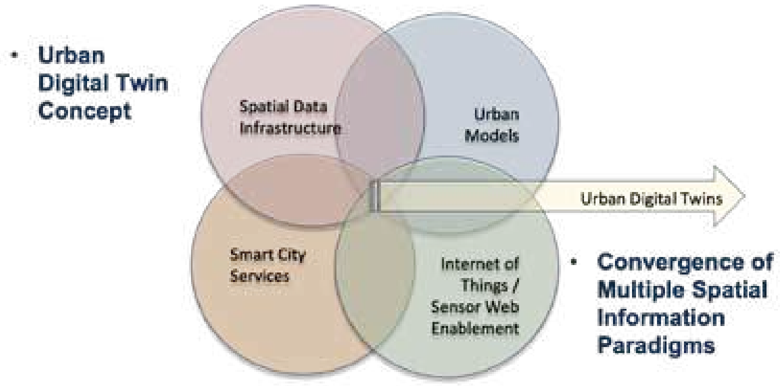

Figure 2-5 | Digital twins as convergence

2.2.2 Location Powers: Urban Digital Twins summit

2.2.2.1 Objective

In January 2021, OGC reviewed many of its innovation initiatives and research and development around smart cities, smart city information and smart city applications through the *Location Powers: Urban Digital Twins* virtual summit. The objective was to identify elements of a research and development (R&D) programme that would contribute to standards development and promote consistent community practices.

2.2.2.2 Location Powers UDT emergent themes

Some of the themes that emerged during the discussion of that work can be seen in Table 2-1.

Table 2-1 | Different themes of Location Powers UDT

No.	Themes
1	3D models are ideal
2	Geographical information systems (GIS) and ethics
3	Values framework and technology
4	UDT are both representations and results of social systems
5	Basis of UDT is standards-based 3D models
6	Sustainable urban twins require standards collaboration, agreement and partnership
7	Visualization
8	Data privacy and security
9	Organizations can develop models independently and use linked data models to federate
10	Different cities have different UDT needs
11	Challenges: arrangements, governance, capacity, awareness
12	Geoempowered people

2.2.2.3 Location Powers UDT recommendations for R&D

The recommendations for R&D covered many of these same aspects, such as fusing underground assets and networks with geology, fusing static and dynamic model ecosystems, system of systems integration and coupling, along with some of the technical issues of how to implent data integration across scale and sector.

2.2.2.4 Location Powers UDT recommendations for standards and practices

The recommendations for standards and practices are listed in Table 2-2.

2.3 Synthesis

CIM is an information technology (IT) concept that is an extension of BIM.

A CIM is an ecosystem of (ideally) integrated IT applications that covers the needs of all the stakeholders involved in urban planning in a smart city.

CIM are data-driven. The data is not only the fuel of a CIM but also a key component of the integration of all its component applications. Thus the need for a city-wide data architecture or model.

Developing a CIM is more than an IT project: it is a reengineering exercise in which silos are broken to facilitate collaborative work in the city.

While the approach of "twinning" was used by NASA in the 1960s with the practice of creating physically duplicated systems at ground level to match the system in space [3], the concept of digital twin (DT) originated in 2002 in the discipline of industrial and mechanical engineering. A digital twin is, succinctly, a digital representation of the "real" world that it is continually mirroring.

The core of a DT involves one or more simulations, i.e. executable models. These models can range from analytics, such as finite element analysis, to rule-based analytics. Added to this core are usually media-rich data acquisition modules and human-machine interfaces. A DT is thus an IT application.

Given the complexity of cities, a UDT will be a federation of digital twins covering different domains (e.g. energy, water, transportation), and using adequate modelling techniques.

Digital twins are data-intensive. Data is required for their construction and then to keep them synchronized with the "real" world. The data used by digital twins ranges from sensor data from the IoT systems embedded in the smart city to transactional data from the city IT systems.

This implies that it would be very challenging to build and maintain UDT without a minimum amount of CIM.

Table 2-2 | Recommendations for standards and practices

Aspects.	Recommendations
Standards	OGC City Geography Markup Language (CityGML) encoding standard for energy and water; underground infrastructure; mobility data standard (MDS) from Los Angeles for mobility data
	Standard "hooks" to federate disparate organizations into a UDT "ecosystem"
	Geoscience Markup Language (GeoSciML) – Towards a common geological data model
	Direct Model for Underground Data Definition and Integration (MUDDI) development towards representation of underground / at grade UDT
	Reduce the complexity of existing standards and focus on integration of multiple domains
	Bring together non-standard data models with those already standardized
	Standards for social systems UDT data (mobility, health, justice)
Community practices	Digital code of ethics
	Advocates "seeded" in each stakeholder organization
	Positioning of UDT as convergence of multiple trends to avoid "cliff of disillusionment" (e.g. not just 5G)
	Foster collaboration by aligning goals of all stakeholders to a higher order purpose and common goal (e.g. sustainability vs standardization)
	Generate interest and demand for UDT through visualization and gamification
	Develop national and/or international UDT hubs that bring together industry, government, academia and NGOs to share UDT best practices
	Build national and international education and training programmes to develop the next generation of geoempowered UDT professionals

Section 3

State of the art of the technologies and practices of city information modelling and urban digital twins

3.1 Technologies and practices of city information modelling

CIM generally is comprised of a 3D urban information complex based on BIM, GIS and IoT technologies, which integrates city data of different spatial scales and time dimensions.

To some extent, CIM can be understood as the expansion of BIM within the city, which refers to the digital expression of temporal and spatial information in communities, regions and cities composed of a single BIM point [4], [5]. BIM also provides CIM with the capability of 3D visualization, the coordination of data sharing, simulation, and dynamic optimization of information.

GIS refers to the collection, storage, management, calculation, analysis, display and description of data related to geographical distribution in the space of the earth's surface (including the atmosphere) [6], which can clearly show the relationship between buildings and the geographical environment and has a strong spatial comprehensive analysis capability [7]. With the help of GIS, CIM can realize a unified spatial coordinate system as well as data management and analysis of 2D and 3D data on a large scale.

Compared with BIM, GIS pays more attention to the ability of macro data management and spatial analysis at the urban scale. Also, GIS, as an important method to describe the city's macro-geographical spatial environment, supports the connection of independent BIM single points in the city.

IoT is a network system based on the Internet and traditional telecommunication networks, which combines various information sensing equipment. It can realize the interconnection of people, machines, and things at any time and place [8], [9]. For CIM, IoT is the sensing source in the physical world and the port for near-real-time data collection of urban operations. It can be considered as the "neural network" of CIM. Through its "dynamic sensing capability", it provides CIM with near-real-time updated urban operating data. The application of IoT in CIM is the key to promoting CIM, from static description to dynamic perception.

The integration of BIM, GIS and IoT technologies enables the implementation of the digital reproduction of physical cities, constructing an objective, near-real-time and sophisticated digital urban spatial entity, namely CIM, which provides a digital foundation for smart planning, construction, management and operation of the city.

In addition, with the development of modern information technology, technologies such as AI and big data have gradually been recognized as key technologies of CIM.

With its powerful data processing capabilities and learning capabilities, AI will become the "central nervous system" of CIM. It will optimize CIM's data recognition capabilities through a large amount of training and learning from the collected government data, corporate data, social data and Internet data [10]. Also, when combined with data training models, CIM's ability to predict urban development trends is improved, so that CIM can realize automatic perception and simulation prediction of urban operating conditions in different time and space.

For example, in the deduction of urban land expansion, users can analyze the historical urban land change pattern data in the CIM platform, and summarize the regular pattern of land use change, so that the change of urban land use in a certain period in the future can be predicted.

The application of big data on CIM solves the data analysis and processing problems of large-scale and complex data sets within CIM. At the same time, considering the technical support requirements of CIM for activities of the entire city, big data provides a series of parameter-configurable thematic evaluation and analysis models, including population, transportation, industry, public services and other fields, to comprehensively improve CIM's intelligent analysis capabilities to various industries (see Figure 3-1).

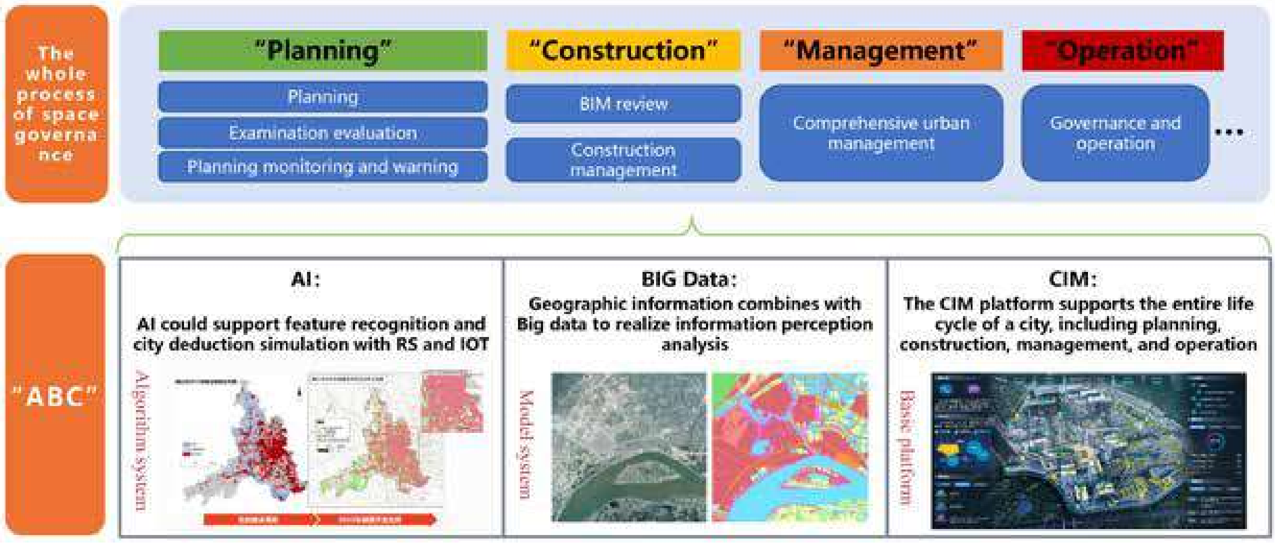

Figure 3-1 | CIM technologies to support space governance

In the practice of CIM, the Ministry of Housing and Urban-Rural Development of China started the preliminary exploration of CIM construction as early as 2018. It selected five pilot areas of Guangzhou, Nanjing, Xiamen, Xiongan New District and Beijing Tongcheng to carry out the construction of the CIM basic platform, which aimed to explore the supporting role of CIM in the detailed governance of smart cities.

Among them, the CIM pilot project in Guangzhou was successfully accepted after two years. The project mainly includes the construction of CIM basic platform and business application scenarios on the CIM basic platform. Among them, the CIM basic platform has integrated the current detailed 3D model and asset information from BIM, addresses, population, houses, units, facilities and other data, and has displayed such data visually. Meanwhile, business application scenarios include housing management, fire inspection, public facilities, urban renewal, urban physical examination, beautiful countryside, key urban construction projects, etc.

Currently more than 10 provinces and cities in China have incorporated CIM construction into their local plans driven by the policy, including Shenzhen, Chongqing, Lanzhou, Tianjin and Foshan. According to the needs of the local professional management, these cities have developed various business application scenarios based on the CIM basic platform. However, these scenarios are mainly in urban construction management (UCM) fields such as planning and design, construction management, environmental monitoring, green building, housing management, emergency management, fire emergency, etc.

In summary, both technically and practically, CIM is still in the early stages. It constitutes an important foundation of smart cities, which means CIM needs to continuously integrate and apply new technologies, such as virtual reality (VR) and blockchain, to adapt to the complexity of urban development. Also, the application of CIM should not be limited to the field of UCM. It is necessary to fully encourage different industry entities in the city to participate in CIM construction, explore in depth the spatial information application scenarios in different industries and build a CIM-based smart city application system. As a consequence, a perceiving, learning, adaptive and well-governed digital urban life entity would take shape.

3.2 Technologies and practices of urban digital twins

The focus adopted here is on the built environment, which covers the micro through to the macro, ranging from buildings, through campuses, with the attendant infrastructure, to cities (see Figure 3-2). What are the differences and similarities to a CIM approach?

The approach implemented has been building-centric and therefore owner-centric rather than government-centric. It has been a BIM-based approach, in which object-based elements from BIM make up the fundamental data elements to which all other data, for example schedule, cost, asset, simulation and performance, is referenced. This does not mean that it is based on model-authoring software from BIM applications. Much data resides in systems that are outside of the main project workflow from BIM, but data keys link all data together through the building life cycle. We refer to this as the digital thread.

There are many practices that are shared and hence symbiotic. The planning of the building needs to consider site selection and hence traffic patterns, the availability of utilities at a price which will support the financial pro forma, and it needs to enable planning issues such as shadow analysis and views to be addressed.

There are also many shared technologies, even though they may be being applied at a micro scale. The digital twins used for the analysis here are based on use cases that provide business benefit. Simulation is applied to support those use cases, and use sensors, both IoT and Internet of Automation (IoA) to understand building, security and people use case performance. The data is collated from those use cases into data lakes and conventional business intelligence and AI is used to provide insight and learning.

The paths involved are similar and to a certain extent parallel, but ultimately, they may converge. When they do, it must be ensured that the convergence will be smooth and so must keep the paths of communication open.

An example of this relationship can be illustrated in a case study in which an owner/developer has a plot of land and needs to produce an optimal design solution that both aligns to the city's strategy and also returns a target profit.

The first step would be to utilize data from a city information model for use in algorithms to drive the building design and commercial analysis. This is the foundation of a built environment digital twin of the proposed development. This means accessing enough relevant high-quality data, easily

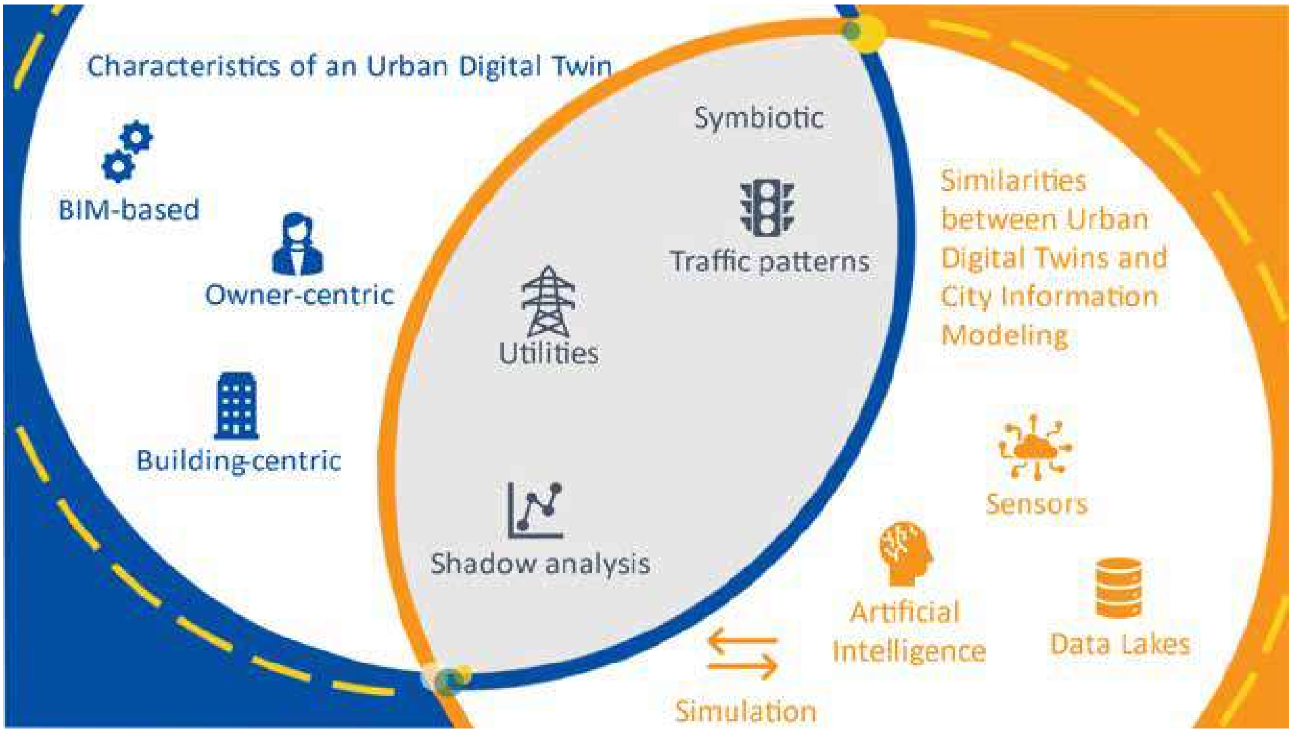

Figure 3-2 | Framework of UDT technologies

and in a timely manner to make informed decisions regarding site and context, and utilizing economic and market data to inform the design.

The key is that the design cannot contravene any planning regulations and must show adherence to city infrastructure plans, or if not, it needs to be very clear on where the design falls short.

From a city perspective, digitalized planning controls are starting to emerge from the more progressive governments and local authorities. Financial, economic and demographic data can be obtained and paid for via the market.

Unfortunately, the process is still facing data silos, and these silos only answer part of the problem. There is still a tremendous amount of manual work involved in connecting this data and ensuring that compliance requirements are met, as well as meeting the needs of a developer/owner. The other challenge is the provenance of data, i.e. ensuring that the data is qualified and accurate.

Unless quality is guaranteed, decisions will always carry risk. It would be ideal if there was some type of centralized authority to certify the quality. Without this, the liability will remain with the owner, and the owner will create their own digital twins, because they can trust their own data.

City and urban design modellers also need to start to answer the harder questions around subterranean digital twins, i.e. geological representation, creating the digital twin of the underground of the city and existing infrastructure to avoid examples in which sites have discovered to their detriment cables/pipes or contaminated land, which results in significant delays and additional costs.

3.3 Synthesis

The description of city information technologies effectively covers three different aspects:

- The information-rich 3D model of the city that is based on the bringing together of BIM and GIS
- The use of IoT to provide CIM with near-real-time updated urban operating data
- Big data technologies and AI to enable the large and complex data sets in CIM to be effectively handled and to enable information about the past and the present to be used to predict the future

BIM provides a way to integrate temporal and spatial information about specific points within the city and affords a means of using the data to develop 3D models. GIS enables these specific points to be integrated to provide a comprehensive picture of the city as a whole and enables the relationship between buildings and the geographical environment to be shown.

IoT enables continual streams of information about the built environment to be collected and brought together and can show the interconnection of people, machines and things in the city at any time and place.

The application of big data technologies in CIM solves the data analysis and processing problems of large-scale and complex data sets within CIM and provides a series of configurable thematic evaluation and analysis models, covering areas such as population, transportation, industry, and public services.

AI optimizes CIM's data recognition capabilities through training and learning from data provided by government, corporate, social networks, and from the Internet. It provides CIM with the ability to better predict urban development trends, and thus enable better planning and management of the city.

CIM is still in its early stages and needs to continue to integrate and apply new technologies, such as VR and blockchain, to adapt to the complexity of urban development. Also, CIM needs to move beyond the current applications, which are very much focused in the field of construction management, to include in-depth application scenarios in different industries and build a CIM-based smart city system that meets the needs of the city as a whole.

Digital twin technologies start with BIM (and GIS) to provide information about the built environment of the city, along with a large amount of data from systems that are outside of the main BIM workflow. A key focus of digital twins is on use cases related to business benefits and the viewpoints of different stakeholders.

Simulations are employed to support those use cases, and sensors, both IoT and IoA, are used to understand use case performance. The data from those use cases is collated into data lakes, and conventional business intelligence and AI are used to provide insight and learning.

One challenge to this framework is that data is still kept very much in silos, and a tremendous amount of manual work is needed to connect it.

Another challenge relates to the provenance of data: how far the data is qualified and accurate. Unless the quality of data can be guaranteed, decisions will always carry risk. It would be ideal if there were some centralized authority to certify the quality.

Section 4

Case studies of city information modelling and urban digital twins

4.1 Developing a city information modelling platform in Nanjing

Nanjing is one of the earliest cities to start the research and practice of CIM in China. This case study will show the work of Nanjing in the past three years, including standards, data, platform and application.

4.1.1 Background

Nanjing is a fantastic, ancient capital and also one of the most innovative cities in China. Faced with the pressure of rapid urban development, there is an urgent need to explore a technological path for high-quality urban development. At the same time, the rapid development of new technologies and the exceptional foundation of Nanjing Smart City provide better conditions for the construction of CIM.

4.1.1.1 Demand-driven

Alongside the advancement of global urbanization, the emergence of “urban diseases” has been a constant challenge. It is very important to develop CIM to help guide cities on the path to smartness, so that changes to help these cities work better do not have unexpected negative impacts.

4.1.1.2 Technology-driven

In recent years, the rapid development of new technologies, such as GIS, BIM, and IoT, has contributed to the innovation and development of smart cities and given birth to the concept of CIM.

4.1.1.3 Policy-driven

Nanjing is a megacity that is the capital of the Jiangsu province of China. During the past decade, Nanjing has successively joined a series of city pilot initiatives in China. These have enabled Nanjing to pursue an approach focused on high quality and have laid a solid foundation for the development of Smart Nanjing.

Therefore, driven by urban development demand, technology innovation and policy guidance, the research and exploration of a CIM platform in Nanjing continues to deepen and grow.

4.1.2 Introduction of the platform

The CIM platform is an important digital infrastructure of the smart city. It is the carrier of data aggregation, service release and application support.

4.1.2.1 Conceptual model

The design and exploration of the initial CIM conceptual model in Nanjing originated from a theory proposed by Zhiqiang Wu, an academician at the Chinese Academy of Sciences. The theory considers that whereas BIM refers to a cell in the city organism, CIM refers to the “city being” or “city organism” as a whole. However, Zhiqiang Wu prefers to call it “city intelligent model”.

The conceptual framework of Nanjing CIM was proposed and designed in terms of three stages: City Information Modelling I, II, and III. City Information Modelling I is similar to the cell. City Information Modelling II is similar to the tissue of the "city being". City Information Modelling III is similar to the flow cycle of the "city being". Through City Information Modelling I, II and III, the evolution from the city cell to the "city being" is realized, and the development of CIM from a primary form to an advanced form is promoted (see Figure 4-1).

Figure 4-1 | Conceptual model of the CIM platform

4.1.2.2 Overall architecture

Guided by the above conceptual model, and based on the principles of "unified standard, unified base map, unified planning and unified platform", the platform has been designed to consist of an infrastructure layer, a data layer, a platform service layer and an application layer (see Figure 4-2).

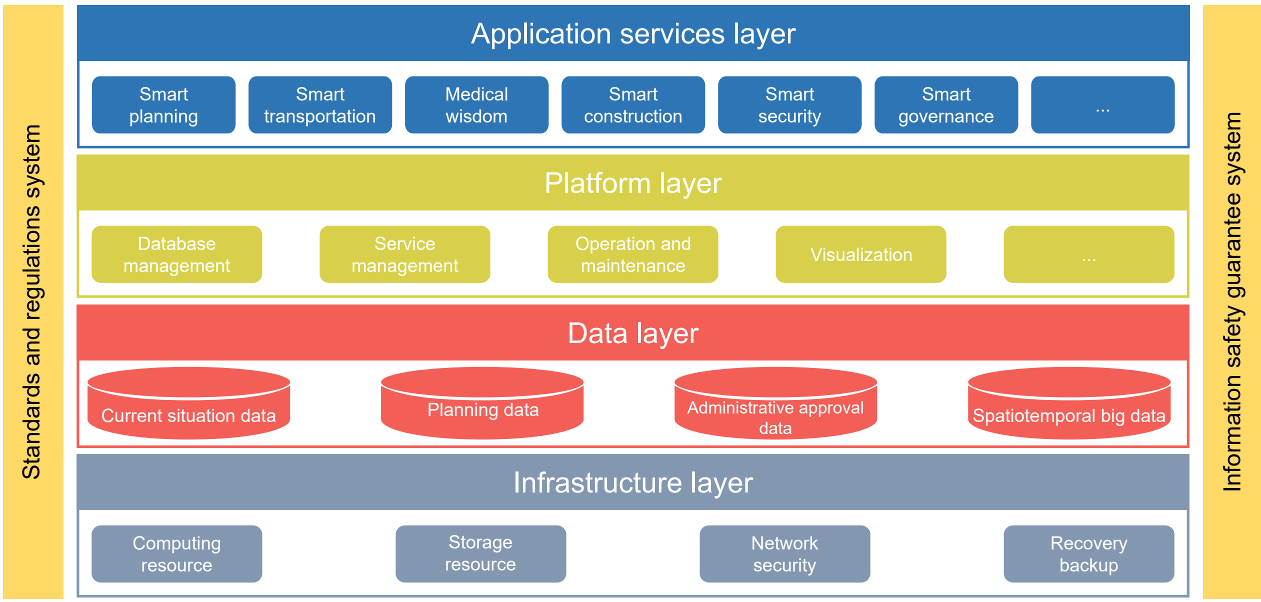

Figure 4-2 | Architecture of the CIM platform

4.1.2.3 Standard system

At the early stage of developing the platform, a pre-study was initiated of Nanjing's CIM standard system. The standard system can be outlined in three levels, eight categories, and 42 types. This set of the CIM standard system is oriented toward megacities such as Nanjing, which have comprehensive sharing and exchange problems. It covers CIM data acquisition, production, and updating and creating of databases, platform services and operations.

4.1.2.4 Data

Under the guidance of the standard system, the platform can deal with rich data that takes asset information models from BIM as the core and smart city as the goal, and integrates multi-source, multi-scale, and full-space information (see Figure 4-3).

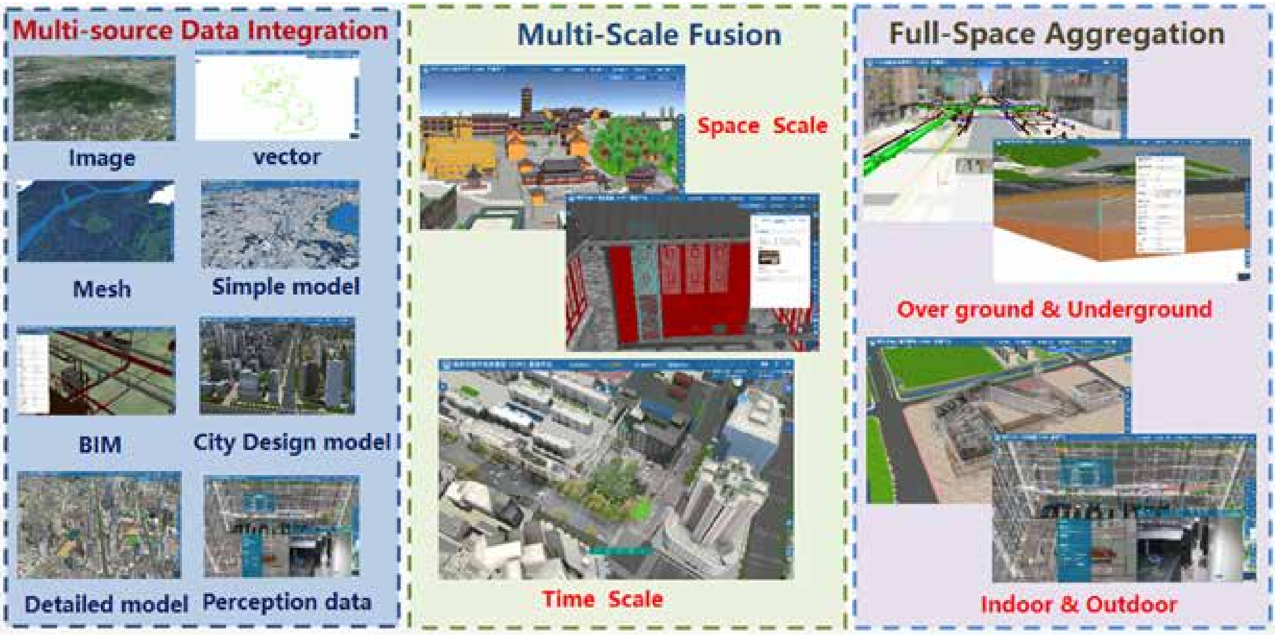

Figure 4-3 | Data basemap of the CIM platform

4.1.2.5 General functions

When equipped with an efficient data engine, the platform supports the fusion and visual expression of massive, multi-source and multi-state data, supports diversified display application requirements, and develops core functions such as analysis and simulation and thematic applications.

4.1.3 Platform applications

The CIM platform can support various activities, such as social and economic development, cultural inheritance, urban planning and construction, ecological protection, etc.

4.1.3.1 Integration and display of spatio-temporal information

The CIM platform can review the past, display the present and embrace the future, as it includes all kinds of spatio-temporal information.

The platform integrates historical data to support the protection of historical and cultural cities. It can display the evolution of historical patterns and urban development processes in Nanjing (see Figure 4-4).

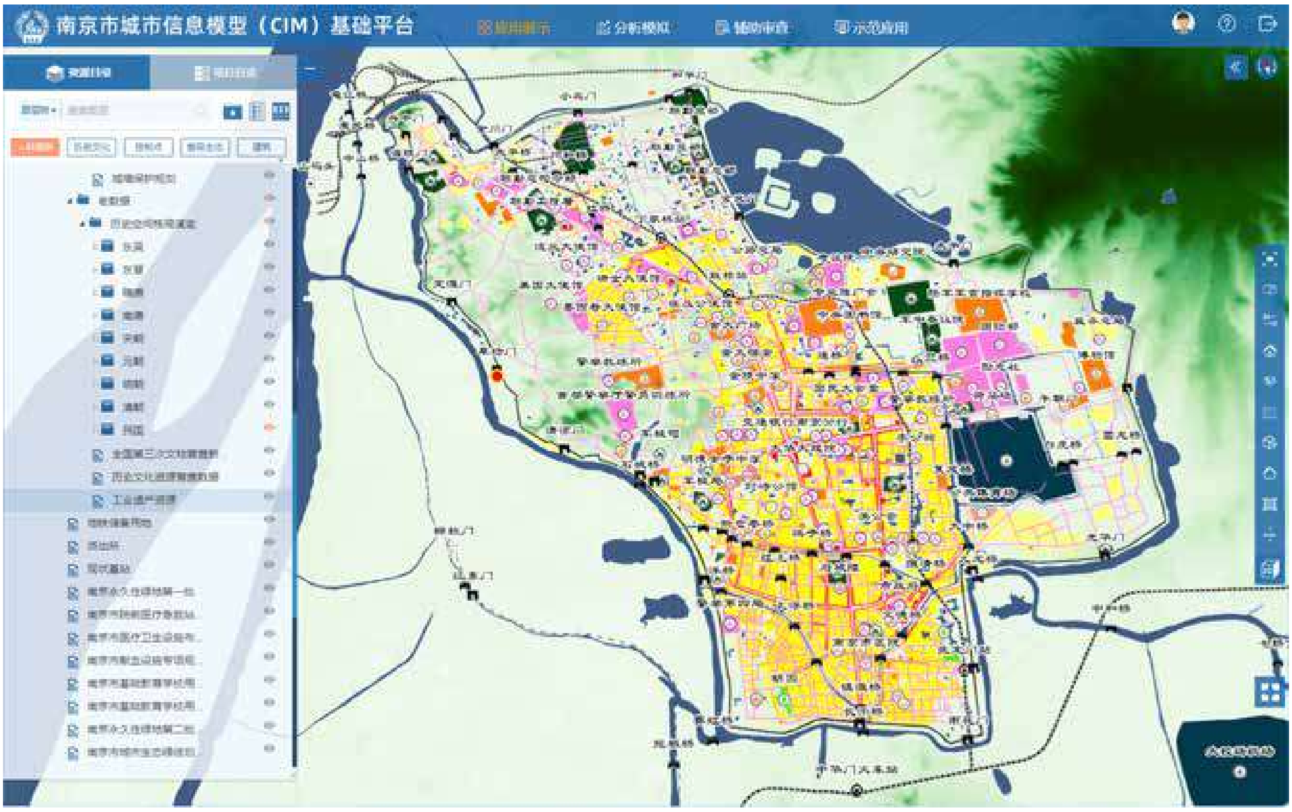

Figure 4-4 | Interface of Nanjing CIM platform for presenting evolution of historical pattern

The platform gathers all kinds of data, such as the current situation, natural landform, management and the social economy. It can better perceive the current situation of the city and provide visual displays and support for city operation and management.

The platform builds intelligent simulation models for urban planning evaluation and prediction. It can coordinate the layout of urban buildings from the perspective of 3D space, coordinate the urban landscape, and provide auxiliary decision-making services for urban planning.

Based on the perspective of both sustainable and intensive urban development, the platform coordinates above-ground, ground, and underground construction, thus carrying out the comprehensive development and utilization of above-ground and underground space.

4.1.3.2 Approval for construction projects during the entire life cycle

CIM provides for the intelligent approval of construction projects during the entire life cycle. For example, it can achieve automatic comparison of design schemes and planning rules, including more than 100 planning conditions such as traffic and building height limits and features, etc. Through the 3D analysis capabilities of multi-plan comparison, managers can be assisted in decision-making and form the optimal design scheme, achieving automatic compliance verification during completion acceptance (see Figure 4-5).

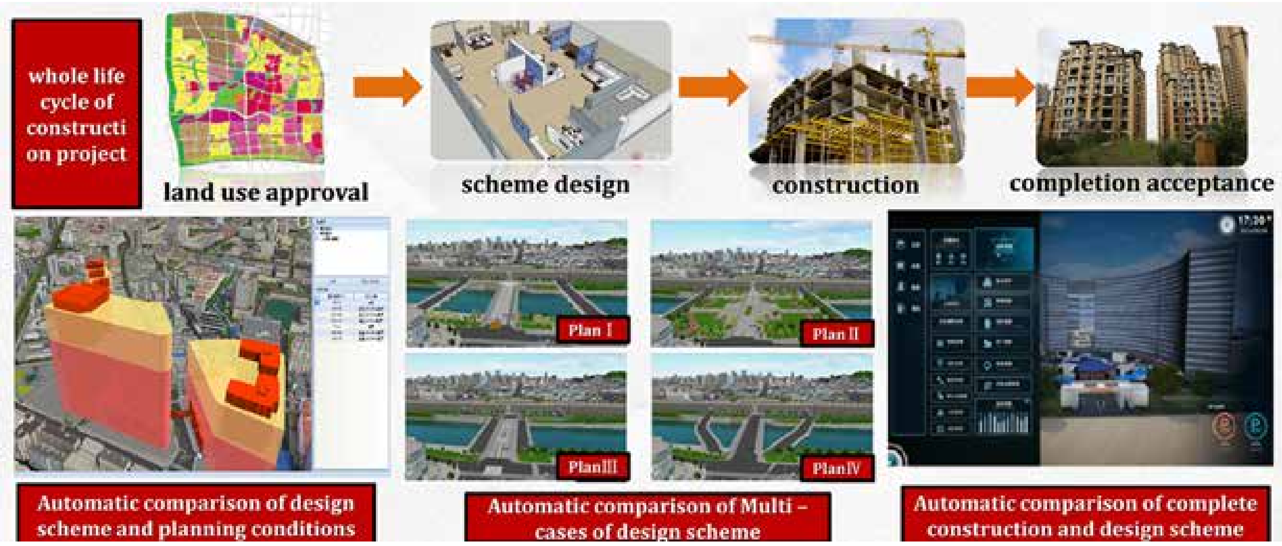

Figure 4-5 | Applying CIM in the whole life cycle of construction projects

4.1.3.3 Registration for real estate

The platform integrates the asset information model from BIM regarding real estate to form a multi-dimensional display and application of an integrated real estate 3D model. The 3D property registration uses CIM to associate ownership data with land information and spatialize massive ownership data accurately. It improves the efficiency and quality of registration services and promotes the government's refined management level.

4.1.3.4 Management of smart buildings

The platform uses IoT technology to access information regarding temperature and humidity, smoke, access control, energy consumption, air conditioning, uniterruptive power supply (UPS) and other equipment. It provides technical support for fire emergencies, energy consumption management, etc.

4.1.3.5 Visualization of video fusion

The platform accesses single or multiple video channels to bring about the convergence between video and real scenes. It brings a combination of dynamic and static scenes and enables the enhancement of information in the real world (see Figure 4-6).

Figure 4-6 | Interface of Nanjing CIM platform for visualization of video fusion

4.1.3.6 Application of "flow" data

The platform analyzes the commercial layout and industrial layout of the city in combination with "flow" data such as population and mobile phone signals. It promotes the optimization of urban spatial layout and improves the quality of urban functions (see Figure 4-7).

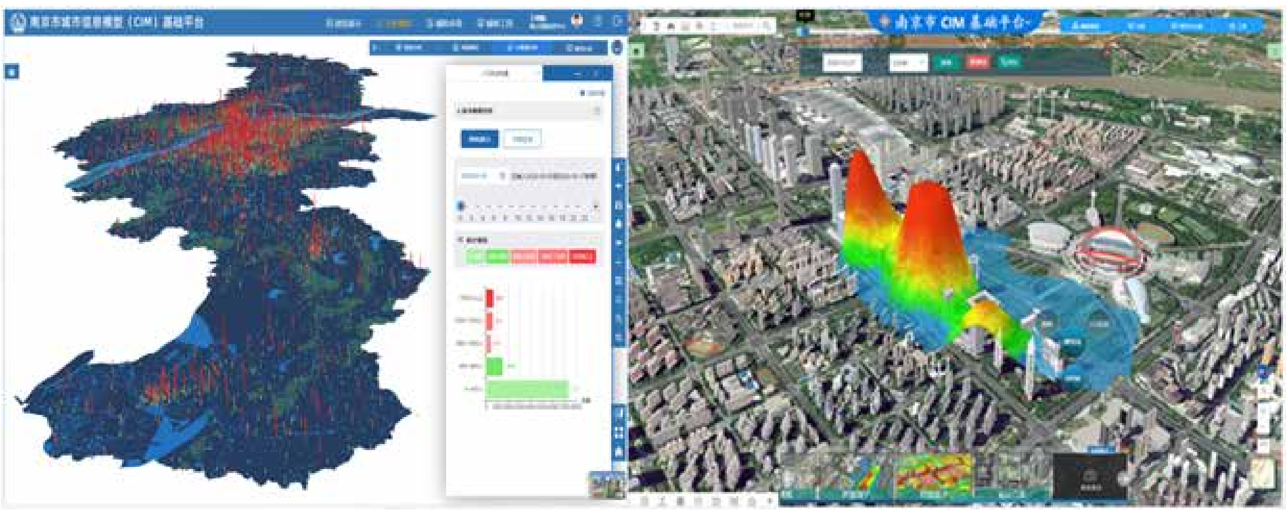

Figure 4-7 | Interface of Nanjing CIM platform for flow data

4.1.4 Work at the next stage

The CIM platform enables the collection and supply of various data and functional services. It can help tackle the problem of information silos, improve the level of urban governance and stimulate the development of the industrial economy. It is the basic platform for smart city construction.

CIM is still in the initial stage. The CIM standard system and standards in the application process will continue to improve, further enhancing the platform capabilities and continuing to comprehensively promote the extensive application of the CIM platform.

4.2 New South Wales spatial digital twin

4.2.1 Geospatial information

For a UDT to "twin" with the real world, the objects, assets and cyber physical systems must be represented by locations on or above the earth's surface. Elements of importance to spatially enabled digital twins reside in several key concepts within geographical information requirements. These key concepts include geographic information service, geographic information system (GIS), location, position, spatial attribute, spatial reference and geomatics.

These concepts and activities provide services that transform, manage and present geographic information to users; are information systems that deal with information concerning phenomena associated with location relative to the earth; provide a particular place or position; hold feature attributes describing the spatial representation of the feature by coordinates, mathematical functions and/or boundary topology relationships; and are a description of position in the real world and the mathematics of the earth.

If we examine the current landscape of digital assets and technologies around digital transformation within organizations, we uncover a variety of heterogenous data sets across many domains.

A relationship that naturally exists between both objects and the occurrences of events and operations is a geographical one. Spatio-temporal aspects of data help to aggregate and filter other data with a geospatial and time-bound context, helping to gather and focus on key constants or variables of a twinned object in space and time.

Spatial techniques enable to take large multidomain datasets and combine them within a visual context. In addition, the application of spatial analysis techniques by the analyst and by users can create unique insights. Large datasets can be broken down into smaller areas of interest with geospatial boundaries for faster computational analysis. The outcomes can be reviewed and assessed before increasing the boundary extents and captured area data. Spatial analysis allows for micro, meso and macro analysis techniques on a variety of vertical domain datasets. Decision-making within urban environments can be supported through standard geospatial analysis techniques related to geographical information analysis.

4.2.2 Urban decision-making

Place-based urban design is becoming an important aspect of city renewal and development projects. These are based both on the specific requirements of the city and suburbs they are targeting, as well as on general aspects that are identified as important to the health, economic sustainability and liveability factors of citizens.

Urban decision-making encompasses a number of such aspects and tools, as identified in Table 4-1.

Table 4-1 | Urban decision-making: focus and tools

Urban decision-making	Spatial analysis tools
Place-based design	Cluster
Land use	Proximity
Planning	Simulation
Liveability analysis	Modelling
Subterranean infrastructure	Nearest neighbour analysis
Resilience planning	Buffer zones
Health	Geometry analysis

4.2.3 Urban issues

Economic considerations for urban environments can be based on land use and property information, as well as on key components and datasets within foundational geographic information. Vertical development and increases in urban density will need to address property, parcel and building considerations including, but not limited to, air space, line-of-sight and shadow analysis. Developments within cities would do well to pinpoint and visualize the precise location of underground utilities and infrastructure data within a spatially enabled digital twin.

Resilience planning for natural disasters and a national and global health crisis can also benefit from the value of current and accurate geospatial data sources. Simulations and physics engine computational analysis can utilize physical and location-based 3D geometries to understand the pathways of environmental forces and their impacts on structural objects within a city. The geometries of structures, their locations and their relationships to other objects are important elements in the twinning of real-world objects and phenomena.

Foundational spatial data are positioned at the base of digital twins as a workbench that supports the vertical domains that operate upon it. The vertical domains have their own specific data that is positioned on the earth's surface and operates in a location-based context. The move can then be made to the aggregation, simulation or scenario testing of spatio-temporal modelling. This opportunity for object and time analysis can provide an opportunity to review past decisions in order to assist in predicating the impact of future decisions (see Figure 4-8).

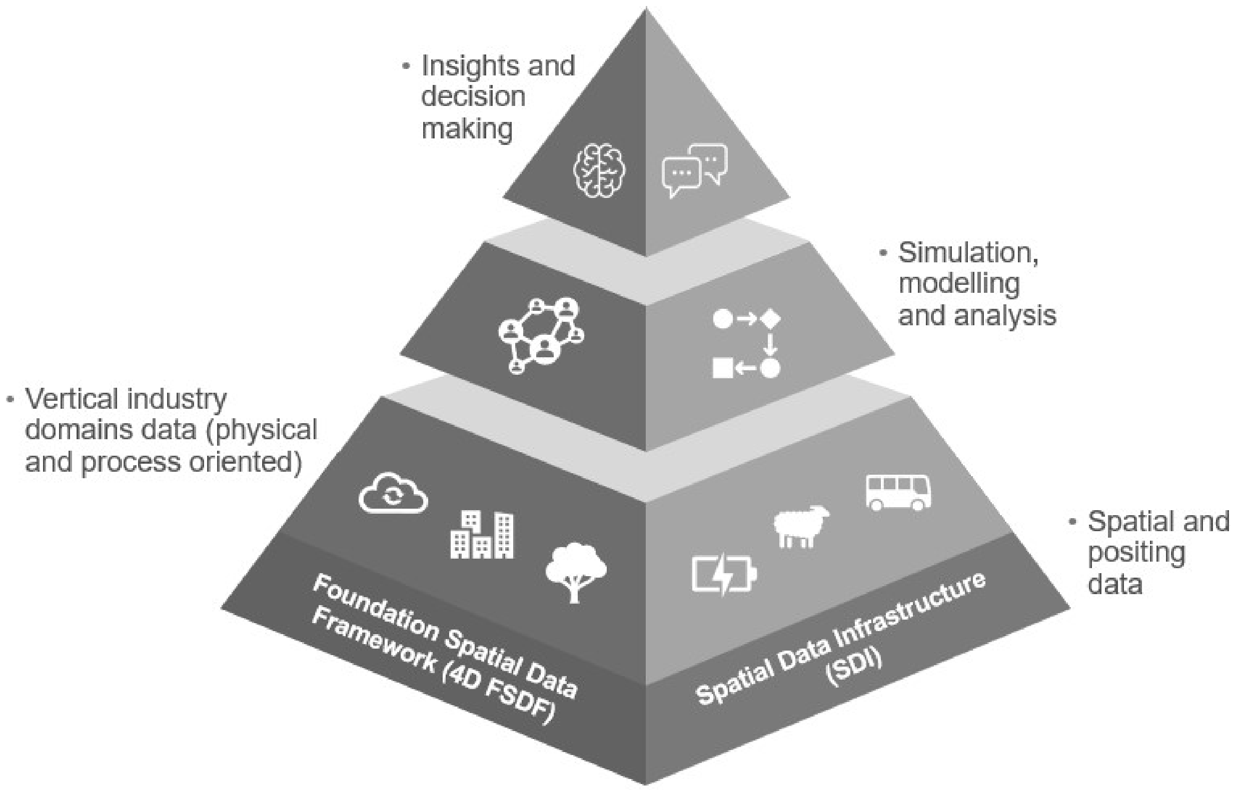

Figure 4-8 | Framework of UDT in practice

4.2.4 Guiding principles

The Australian and New Zealand Land Information Council (ANZLIC) identifies 10 themes through which foundation spatial data can be grouped. These common location data themes aim to "serve the widest possible variety of users" [11]. The 10 themes under the Foundation Spatial Data Framework (FSDF) include: geocoded addressing, administrative boundaries, positioning, place names, land parcel and property, imagery, transport, water, elevation and depth, and land cover and land use. The objective of the NSW spatial digital twin is to deliver enhanced FSDF as 4D (3D + time)- enabled datasets to a spatial digital twin ecosystem.

The principles guiding the NSW spatial digital twin drew on both the Gemini Principles of the UK's Centre for Digital Built Britain [12] and the FAIR (findable, accessible, interoperable and reusable) principles [13]. The nine principles presented by ANZLIC provide a common set of guiding principles for the development of digital twins and spatially enabled digital twins across Australia. These principles include public good, value, quality, adaptation, openness, security and privacy, curation, standards, and federated models [14].

4.2.5 NSW spatial digital twin

The NSW spatial digital twin platforms and ecosystems provide key source datasets such as geocoded addressing, administrative boundaries, positioning, place names, land parcel and property, imagery, transport, water, elevation and depth, and land cover and land use data, as well as a platform interface for adding domain specific datasets by the user.

Multiple datasets can be added to the visual environment, depending on the available datasets within that area of interest. These datasets can be accessed through an open data catalogue. Data available has both a 3D visualization geometry or symbology and associated key attribute values of the feature. For time or 4D-enabled datasets the user can select a date in the past and compare with present data through a split screen capability of the user interface. The user may utilize a login feature that links to a federated data ecosystem, requiring authentication for access to secured datasets. Other features include the creation of spatial data story boards for location-based projects and presentations; time of day slider for shadow casting visual analysis; metadata information and access to downloadable data or application programme interface (API) endpoints. The NSW spatial digital twin can facilitate both the inclusion of user data onto the platform environment as well as a catalogue to provide data downloads and APIs for inclusion into a user discrete digital twin ecosystem.

4.2.6 Summary

The importance of geospatial data and information within the areas of UDT is seen not only from a visualization perspective but also for the data contextualization and benefits of various vertical domains data analysis. The data and ecosystems enable the ability to gather datasets and perform various spatial analysis techniques, and offer an opportunity to utilize and connect key spatial data to other discrete digital twin ecosystems.

Spatial data enables micro, meso and macro relationships to be positioned, aggregated and analyzed. Space, place and time are part of a system-of-systems approach to understanding and improving the urban environment. Everything happens somewhere, and only with foundational spatial data can the where be specifically known.

4.3 The Greater Hobart Region and digital twins

4.3.1 Introduction

The purpose of developing the business case for the digital twin was to provide advice to the Greater Hobart City Deal Implementation Board as to the high-value opportunities to be unlocked through the development of a transformative digital infrastructure for Greater Hobart.

The creation of a Greater Hobart Digital Twin (GHDT) has the potential to deliver the digital infrastructure necessary to maximize benefits and remove friction from the delivery of the Greater Hobart City Deal's significant infrastructure programme.

4.3.2 Why Greater Hobart needs a digital twin

Greater Hobart is experiencing unprecedented growth, with increasing numbers of visitors and new residents every year. The economy, in particular the construction sector, is thriving. This wave of population growth is increasing the pressure on the region's legacy social infrastructure, including housing affordability and services, and is also impacting on the natural environment.

The Hobart City Deal is a shared, 10-year vision between the Australian and Tasmanian Governments and the Clarence, Glenorchy, Hobart and Kingborough Councils. The City Deal will embrace opportunities for growth and for creating a smart, liveable and investment-ready city, while addressing emerging challenges such as housing affordability, urban renewal and improvements to a lagging transport system.

The commitment to deliver the City Deal, create a more liveable region and drive economic development will demand a new way of working across the four Greater Hobart metro councils, including in collaboration with their key stakeholders. To help Greater Hobart reach these objectives three key problem areas must be addressed:

- **Digital reform**

There is a need to embrace digital sharing as a means of overcoming competing local governments' challenges. The current lack of digital service integration across the local government authorities (LGAs) is a key non-structural impediment to joint, cross-boundary service opportunities. Strategic planning and joint investment opportunities are constrained as a result.

- **Multi-modal visualization**

There is a need to create a more liveable region, where quality of life is achievable through equitable housing and mobility options, attractive open spaces, high environmental quality and personal safety. Without a tangible operational model to combine cross-sector data and information (e.g. home building, commercial and industrial developments and transport planning) holistic cross-boundary precinct planning remains constrained.

- **Dealing with economic investment friction**

There is a need to encourage economic growth by attracting investors from all sectors: an approach inclusive of, but agnostic to, the strategic imperatives of individual local authorities. To undertake such decisions, investors, both foreign and domestic, require access to a broad range of data, which is currently not visible to them. This lack of easily available, visual and easy-to-interpret data adds friction to decision-making and creates significant barriers to future investment.

4.3.3 What is the Greater Hobart Digital Twin vision?

A digital twin is a collection of disparate information made available within a computer-generated digital representation of complex and sophisticated built environments. It is capable of providing historical, near-real-time and future interactive spatial views of multiple datasets simultaneously, as a basis for superior decision-making.

The GHDT will provide a single environment and common interface through which local, state, and Australian government authorities, the public, commercial investors and many other stakeholders will be able to interact with key service data associated with the four Greater Hobart Councils.

In short, it will transform ways in which the region can sense and respond to, as well as predict and act on, strategic and operational activities to dramatically improve decision-making capabilities.

Local government and government business stakeholders will be able to access, on a sophisticated and secure permissions basis, all archived and near-real-time data shared by the State Government and the four local government authorities within a single environment, opening up access to that data and giving insight across all key services.

Private investors including manufacturing and tourism developers will be able to rapidly understand and make quicker investment decisions by having the data made easily available to them.

The Greater Hobart public will be able to interface with the digital twin by accessing data from a range of services, including the proposed digital bus shelters that will enable them to search for bus routes, find sights to see in the area, optimize their route planning and receive live service updates on key government services.

4.3.4 Digital twin customers and how they will use the infrastructure

- **Council stakeholders**

The GHDT will provide local government stakeholders with the ability to access federated structured data sets in a single point of view to help deliver better key services.

The digital twin will provide a digital visualization in which planned housing, urban renewal and transport developments can be overlaid against the existing built environment to simulate and visualize combinations of potential future developments.

- **The public**

The GHDT will deliver a unique service experience to citizens and tourists by providing two-way interaction with the digital twin. Examples of interaction and human interface will include a phone app and a smart bus shelter.

Smart bus shelters are an example of an enhanced human interface with the digital twin. Citizens and tourists can “pull” data, employing the bus shelter functions to search for bus routes, find sights to see in the area, optimize their route planning and receive live service updates.

- **Commercial investors**

The GHDT will provide developers/investors visibility to key datasets needed for investment decisions. The DT portal will provide tourism service providers with access to a broad range of detailed data to undertake investment appraisals, for example, regarding tourist density and demography, footfall, peak periods and location, etc.

4.4 Synthesis

The city of Nanjing is one of the leading smart cities in China and is keen to avoid the “urban diseases” that can result from rapid urban development. Because of this, it has built, and continues to extend, a comprehensive CIM platform.

The platform has been designed to include three stages. The first stage is based on BIM and can be considered to refer to individual cells in the city organism. The second stage shows how the different parts of the city link together – the tissue of the city organism. The final stage extends this to show the flow cycles of the city organism.

The platform can bring together information from many sources, display and analyze it at many different levels of spatial and temporal scale, and cover what is above and below ground and both inside and outside of buildings.

It is particularly focused on the planning and management of new construction in the city and can help with every single stage from design to completion. It is also able to provide near-real-time insight into the flows of people and supplies around the city. However, this is seen as just the beginning of a process to help support every aspect of city life.

The NSW spatial digital twin is being developed to use data to link real world objects and systems to specific locations. This is partly to support visualization of the data but also to enable the data to be contextualized: for instance, to link data from an air quality sensor to the fact that it is near a busy road, or an industrial estate. Linking datasets geospatially enables the use of various analysis techniques and provides the opportunity to utilize and connect key spatial data to other discrete digital twin ecosystems.

A key value of a spatial digital twin comes from the fact that place-based urban design is becoming an important aspect of city renewal projects. This recognizes that the design of new developments needs to be based not only on the specific requirements of the city and suburbs they are targeting, but also on aspects important to citizens, such as health, economic sustainability and liveability. The NSW spatial digital twin enables many such spatially based data sets relevant to the planning process to be accessed through an open data catalogue.

A digital twin is being developed in **the Greater Hobart area of Australia** because it is experiencing unprecedented economic growth, with increasing numbers of visitors and new residents every year. This is increasing pressure on the region’s social infrastructure, including housing affordability and services, and is also impacting the natural environment.

The digital twin will address three key problems:

- the need to embrace digital sharing as a means of overcoming competing local governments' challenges;
- the need to combine cross-sector data and information (e.g. home building, commercial and industrial developments and transport planning) to support holistic cross-boundary planning;
- the need to provide potential investors with access to a broad range of easily available, visual, and easy-to-interpret data.

It will also allow the public to access data from a range of services, to search for bus routes, find sights to see in the area, optimize their route planning and receive live service updates on key government services.

Section 5

Standards work of city information modelling and urban digital twins

5.1 Standards roadmap

As the UK continued its journey towards digital transformation for the built environment, its National Infrastructure Commission (NIC) set out to establish the key considerations when generating and collecting information about national infrastructure in *Data for the Public Good* [15]. That report set out actions in three areas: collecting the right data, setting standards for data, and sharing that data securely. Within these actions was the recommendation for a roadmap to establish a national digital twin of the UK's infrastructure. The following year, the Centre for Digital Built Britain (CDBB) published both *The Gemini Principles* [12], which provided a definition and a recommended set of principles for such digital twins, as well as *The Roadmap for Delivering the Information Management Framework for the Built Environment* [16].

With the need for standards established, both within *Data for the Public Good* and within *The Roadmap for Delivering the Information Management Framework for the Built Environment*, CDBB engaged with the British Standards Institution (BSI) to undertake a standards landscaping activity as well as to establish a standards roadmap.

Through quantitative analysis of national and international standards (current and in development), a schedule of standards which support different aspects and elements of digital twins for the built environment was produced. After establishing the search criteria, approximately 12 500 standards were identified which, following a relevancy exercise and the omission of duplicate entries, was refined to approximately 2 500 unique standards categorized into the following areas of focus: data, information and communication technology (ICT), application and outcome (see Figure 5-1).

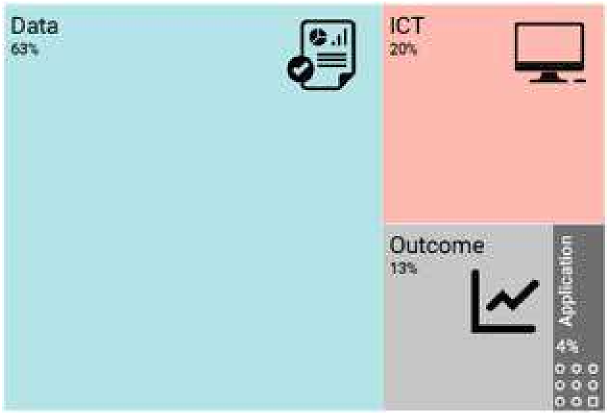

Figure 5-1 | Standards landscape by area of focus [18]

Due to the search criteria used, several standards appeared multiple times. For example, ITU-T Y.4461, *Framework of open data in smart cities* [17] appeared in several searches, as it related to key topics such as data security, data openness and performance outcomes.

Of these standards, the vast majority related to data, reinforcing a well-known factor about the degree of standardization within the field of data, including data quality, data openness, data structure and data security. While data was shown to be well standardized, it was apparent that the other areas of focus had a lower degree of standardization and may present opportunities for further standardization.

To explore such opportunities, BSI proceeded to undertake a qualitative analysis using in-house subject matter expertise to identify priority areas for further standardization. In doing so, several recommendations were made including a four-part *Digital twin framework for the built environment*:

- Part 1: Overview and general principles
- Part 2: Reference architecture
- Part 3: Digital representation of built environment elements
- Part 4: Information exchange

More than eight "related" publications were developped to support the application of the framework as well as the wider digital transformation of the built environment.

In recognition of the current standardization work being undertaken within ISO/IEC JTC 1/SC 41: Internet of things and digital twin, as well as the work being undertaken within ISO/TC 184/SC 4: Industrial data, the *Digital twin framework for the built environment* was proposed as a means of having a series of standards that outline built environment requirements, which could sit underneath the pan-sector domain currently being established within ISO/IEC JTC 1 (see Figure 5-2].

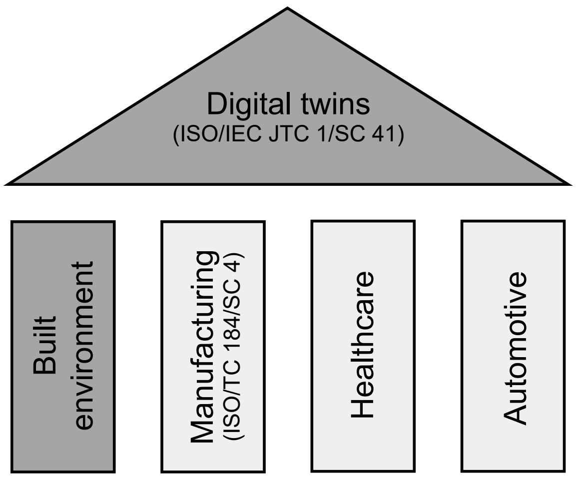

Figure 5-2 | Digital twin domains [18]

In addition, this recommendation intentionally mirrors the structure of the ISO 23247 series [19-22] within ISO/TC 184/SC 4.

In doing so, it was hoped that the requirements of manufacturing and the built environment could be read holistically. This would provide several benefits in scenarios where their respective domains interface, such as modern methods of construction as well as the generative design and pre-fabrication of construction elements.

Once the recommendations were established, their dependencies and key related standards were identified to form a roadmap which was published within *Digital Twins for the Built Environment Standards Roadmap – 2021* [18] on the CDBB Digital Twin Hub. A simplified view showing only the recommended standards is shown in Figure 5-3.

The roadmap and its recommendations were tested with UK digital twin stakeholders who responded positively, with a strong desire to prioritize the work to establish an overview and general principles. In response to this, work is now underway on producing a standard describing the overview and general principles of digital twins for the built environment. This standard is being produced by BSI through its agile standards development approach as BSI Flex 260.

It is hoped that the UK will support the development of the other parts of the *Digital twin framework for the built environment* as well as the other recommendations relating to digital readiness, process modelling, interoperability and holistic asset management. Support would include the development of national standards as well as proposing some of these recommendations to CEN/ISO/IEC to be developed internationally.

Further information on the UK work relating to digital twins for the built environment can be found at https://digitaltwinhub.co.uk.

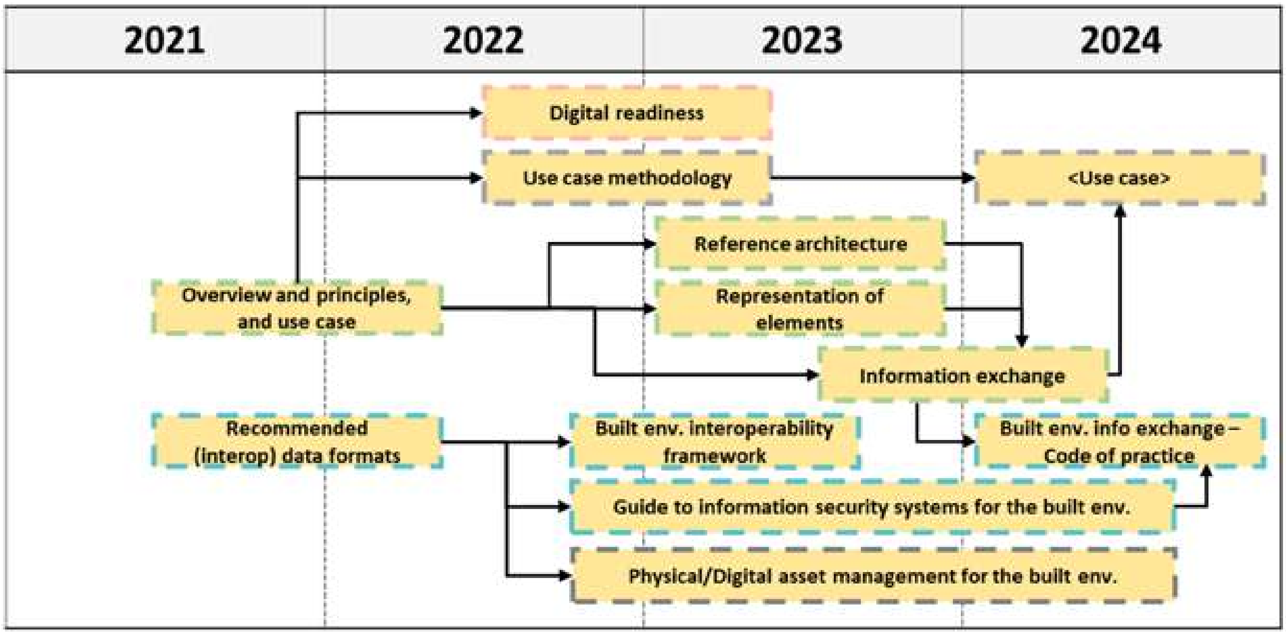

Figure 5-3 | Recommendation dependencies diagram [18]

5.2 Developing a digital twin reference architecture: example of smart manufacturing

In this subsection, the definition of digital twin studied in ISO/IEC JTC 1/SC 41/WG 6: Digital twin, an overview of the digital twin-related standards developing organizations (SDOs) and consortia, the digital twin manufacturing framework studied in ISO/TC 184 and its corresponding implementations are presented (see Figure 5-4).

As discussed in ISO/IEC WD 30173, *Digital twin – Concepts and terminology*, a digital twin is a digital representation of a particular physical entity or a process with data connections that (1) enable convergence between the physical and digital states at an appropriate rate of synchronization, (2) has the capabilities of connection, integration, analysis, simulation, visualization, optimization, and (3) provides an integrated view throughout the life cycle of the physical entity or the process.

Digital twin draws a lot of attention in standardization organizations and consortia. On the aspect of support technologies, the realization of digital twin depends on geomatics, simulation, IT technologies such as IoT, big data, cloud computing, AI, IT security and so on, product property, AR/VR and many more. On the aspect of application areas, with the trend of digital transformation, digital twin is widely applied in smart cities, smart manufacturing, smart energy, healthcare, etc.

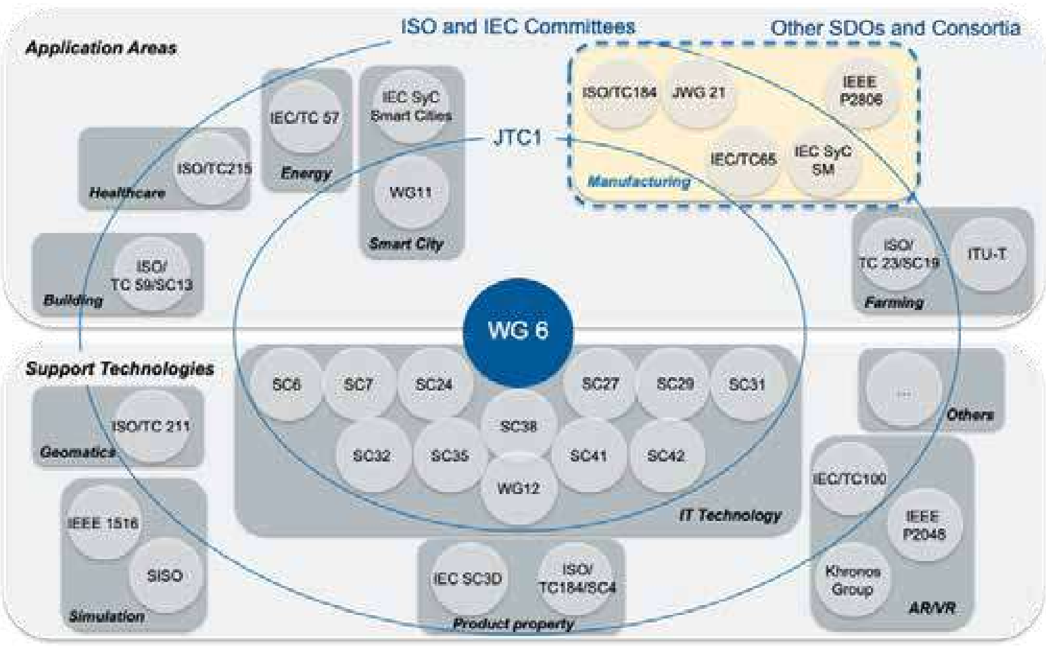

Figure 5-4 | ISO/IEC JTC 1/SC 41/WG 6 and digital twin-related SDOs and consortia

Specifically, for smart manufacturing, ISO, IEC, ISO/IEC JTC 1 and IEEE all have working groups and projects discussing the technical requirements of digital twins in the manufacturing environment. JTC 1/SC 41/WG 6 mainly focuses on building general digital twin tools to support different verticals and has built liaisons with these relevant SDOs (see Figure 5-5).

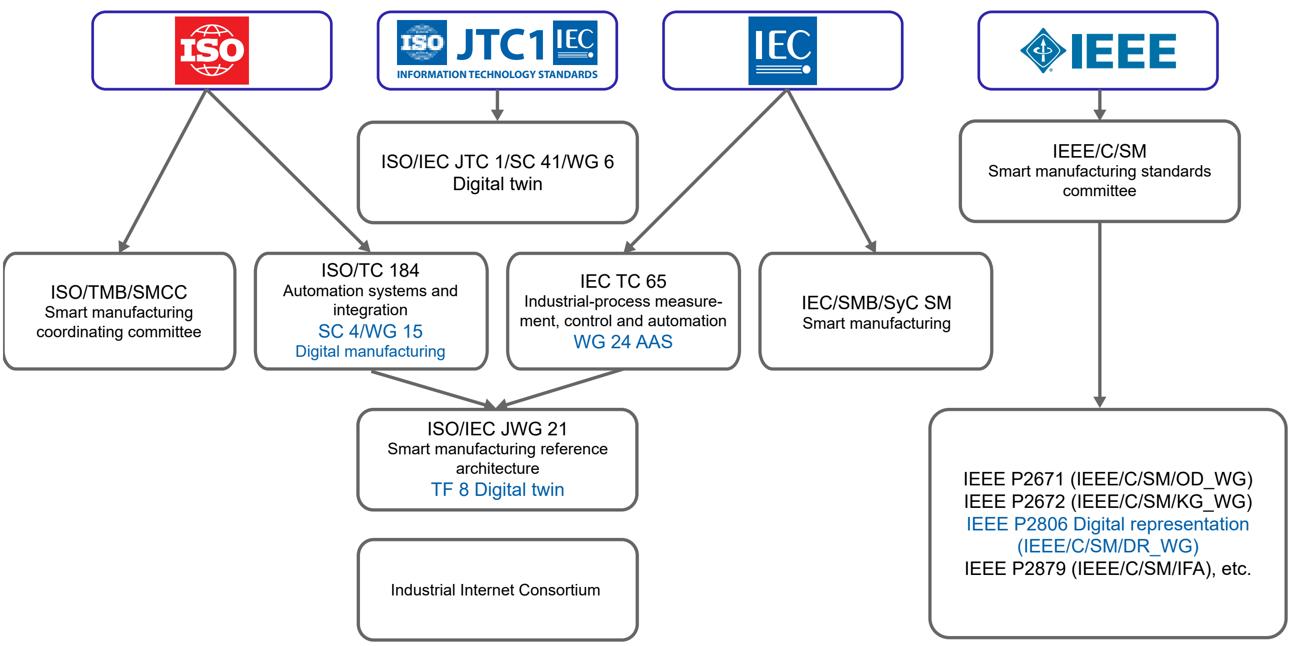

Figure 5-5 | Standardization organizations on smart manufacturing and digital twin

ISO/TC 184/SC 4/WG 15 has developed two related series standards, in which ISO 23247 [19-22] focuses on the digital twin manufacturing framework and ISO 24464 [23] analyzes visualization elements of digital twins. The remainder of this subsection takes a close look at the achievements of ISO 23247.

This series standard follows the methodology of ISO/IEC/IEEE 42010:2011 [24], from conceptual model to reference model to reference architecture, with the functional viewpoints, network viewpoints and implementations viewpoints being given, respectively.

In the first step, a high-level concept of digital twin manufacturing is illustrated (see Figure 5-6). Here, digital twin and the physical world are connected and synchronized through a data collection and device control medium. A digital twin is context-dependent and could be a partial representation of a physical system. It may consist only of relevant data and models that are specifically designed for their intended purpose.

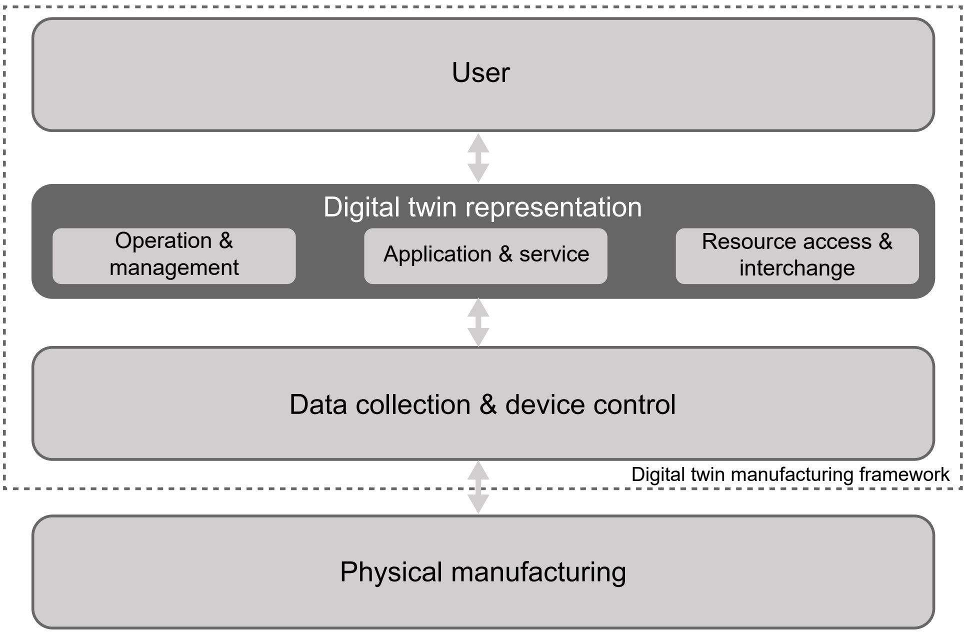

Figure 5-6 | Concept of digital twin manufacturing framework in ISO 23247-1 [19]

In the second step, reference to the IoT reference model defined in ISO/IEC 30141 [25], a domain-based digital twin reference model, is introduced. Four domains are covered (see Figure 5-7), of which the digital twin manufacturing framework covers three categories: data collection and device control domain, digital twin representation domain, (which could be further divided into three subdomains, namely, operation and management sub-domain, application and service sub-domain and resource access and interchange sub-domain) with the user domain lying on the top of the model.

Operation and management sub-domain is responsible for provisioning, managing, monitoring and optimization of the DT representation domain. **Application and service sub-domain** is responsible for applications and services such as simulation, analysis, etc. **Resource access and interchange sub-domain** manages access to entities of the digital twin manufacturing framework and interaction with external entities such as peer DT representation domains by guaranteeing interoperability.

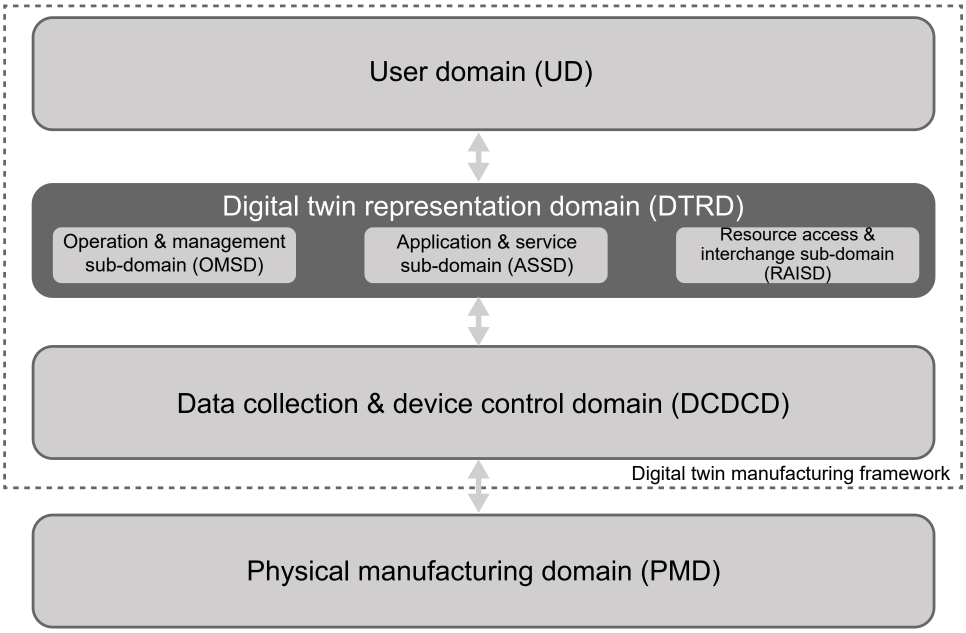

Figure 5-7 | Domain-based digital twin manufacturing reference model in ISO 23247-2 [20]

The standard also gives an entity-based digital twin manufacturing reference model and a domain-entity mixed reference model. From the bottom of the entity-based digital twin manufacturing reference model (see Figure 5-8), **physical manufacturing element** (PME) is an observable manufacturing element in production that shall be monitored and sensed and may be actuated and controlled by **data collection and device control entity** (DCDCE). **Data collection and device control entity** interacts with the PME by monitoring, sensing, controlling and actuating. It also communicates with the **digital twin representation entity** (DTRE), for support in generating, synchronizing and managing digital twins. Finally, the **cross-system entity is an entity** that resides across domains and stretches to digital twin manufacturing framework to provide common functionalities.

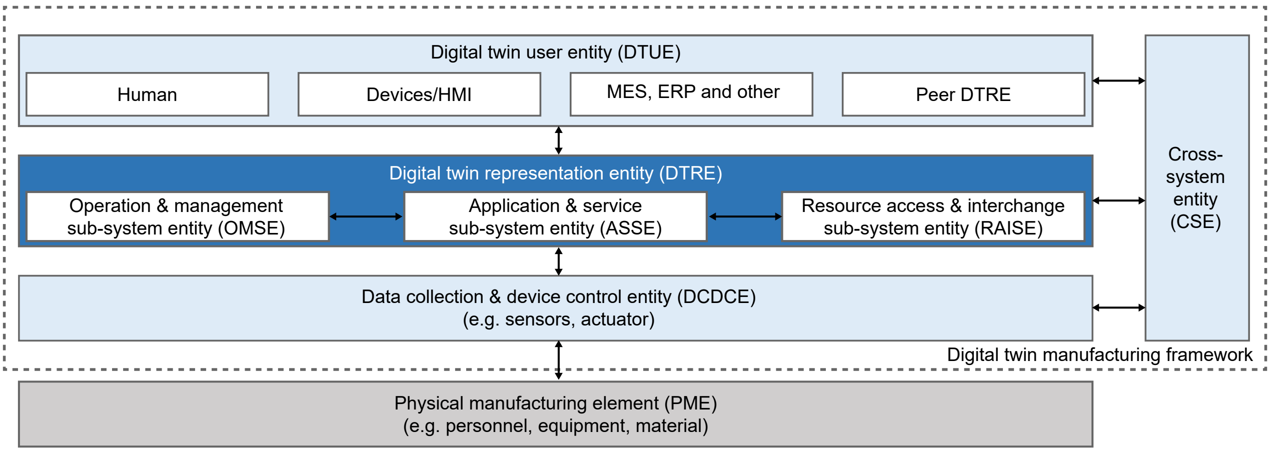

Figure 5-8 | Entity-based digital twin manufacturing reference model in ISO 23247-2 [20]

Likewise, there exists the domain-entity mixed reference model (see Figure 5-9), in which the domains and entities can be extended, merged or added depending on practical use cases.

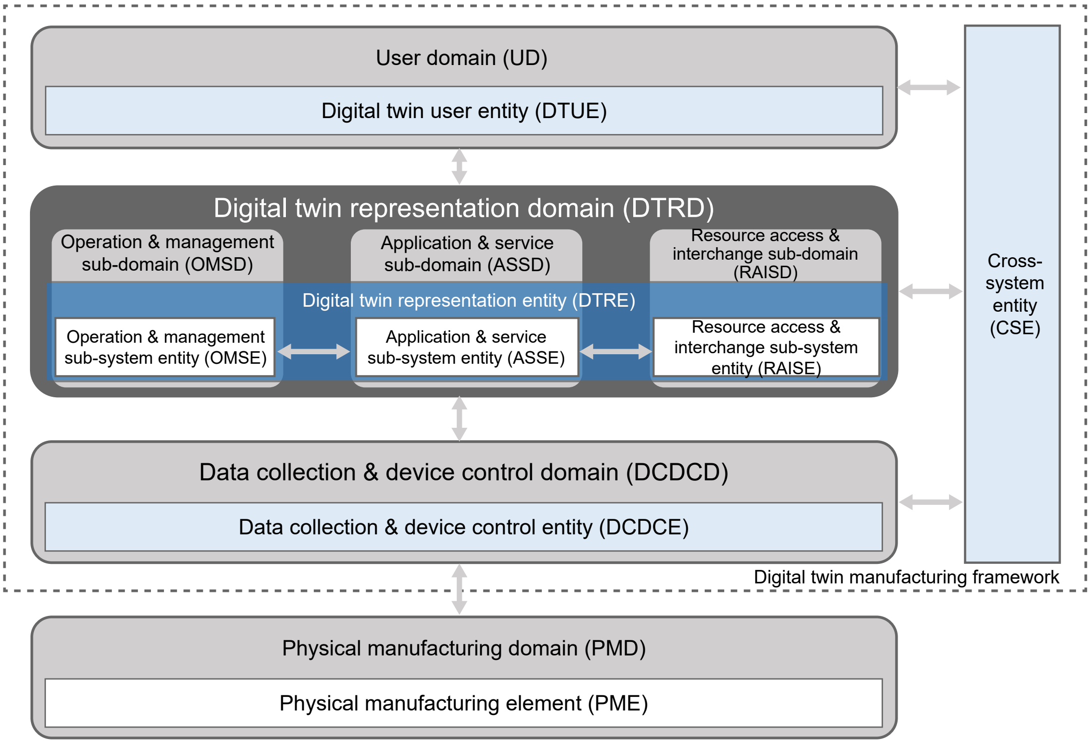

Figure 5-9 | Domain-entity mixed digital twin manufacturing reference model in ISO 23247-2 [20]

In the third step, the **digital twin manufacturing functional view** is given. Take the operation and management sub-system entity as an example. **Synchronization FE** (functional element) provides functionality of synchronizing the status of the visualized digital entity with the status of the observable manufacturing element, or vice versa. **Presentation FE** provides functionality of presenting an observable manufacturing element as a digital entity in conjunction with digital modelling FE. **Digital modelling FE** provides functionality of interpreting information of the observable manufacturing element to understand its physical properties, status, etc. **O&M support FE** provides functionalities of operating and managing DTRE (see Figure 5-10).

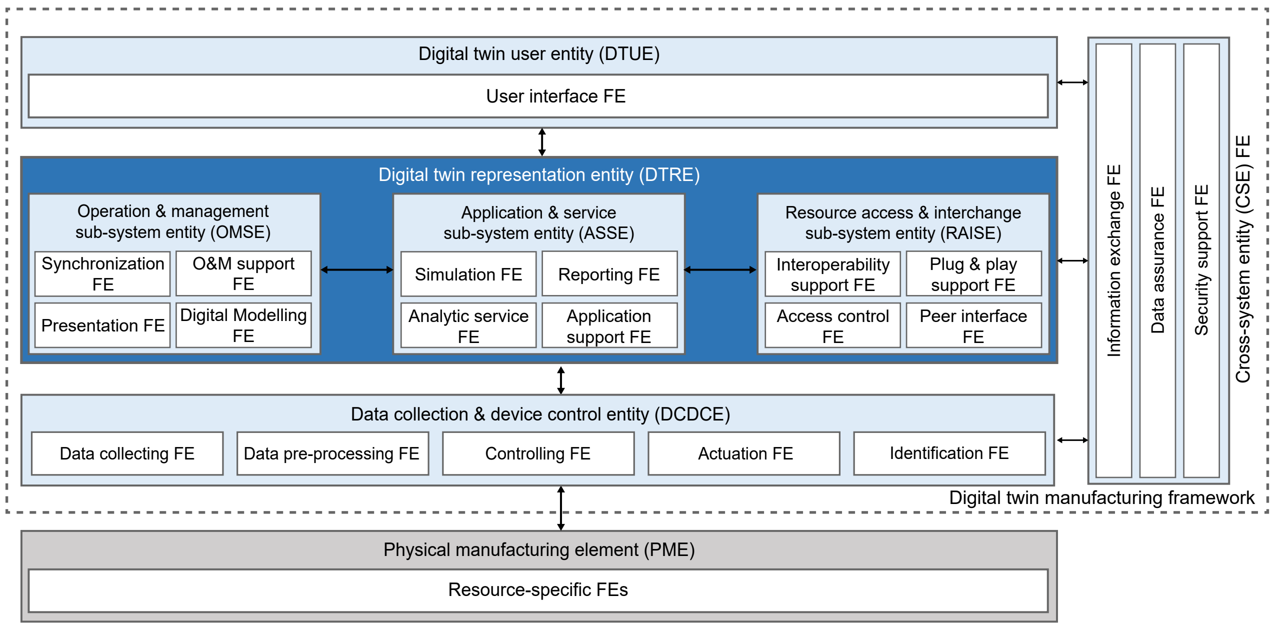

Figure 5-10 | Functional view of digital twin manufacturing reference architecture – decomposition into functional entities in ISO 23247-2 [20]

Fourthly, the networking reference architecture view (see Figure 5-11), which describes communication networks, is given. Typical examples of a transmission network can be wired communication such as LAN and wireless communication such as WLAN and mobile (cellular) networks, which generally adopt IP-based communication protocols regardless of communication type. **Information exchange** between DCDCE and DTRE over the transmission network is supported by appropriate communication protocol.

Finally, implementation options for four information exchanges (IE) using various existing protocols and mapping of digital twin with source data are given (see Figure 5-12). Take IE-A as an example. The IE-A is an interface between the digital twin user entity (DTUE) and the digital twin representation entity (DTRE). Through IE-A, DTRE can provide results from the services and applications of the digital twin to the DTUE. Regarding the standardized method for data exchange, DTRE can provide web service for the DTUE to use services provided by DTRE through web interface using HTTP or REST within IE-A. The data format that can be used includes JSON, XML, etc. DTRE can also define open APIs to access services from the digital twin.

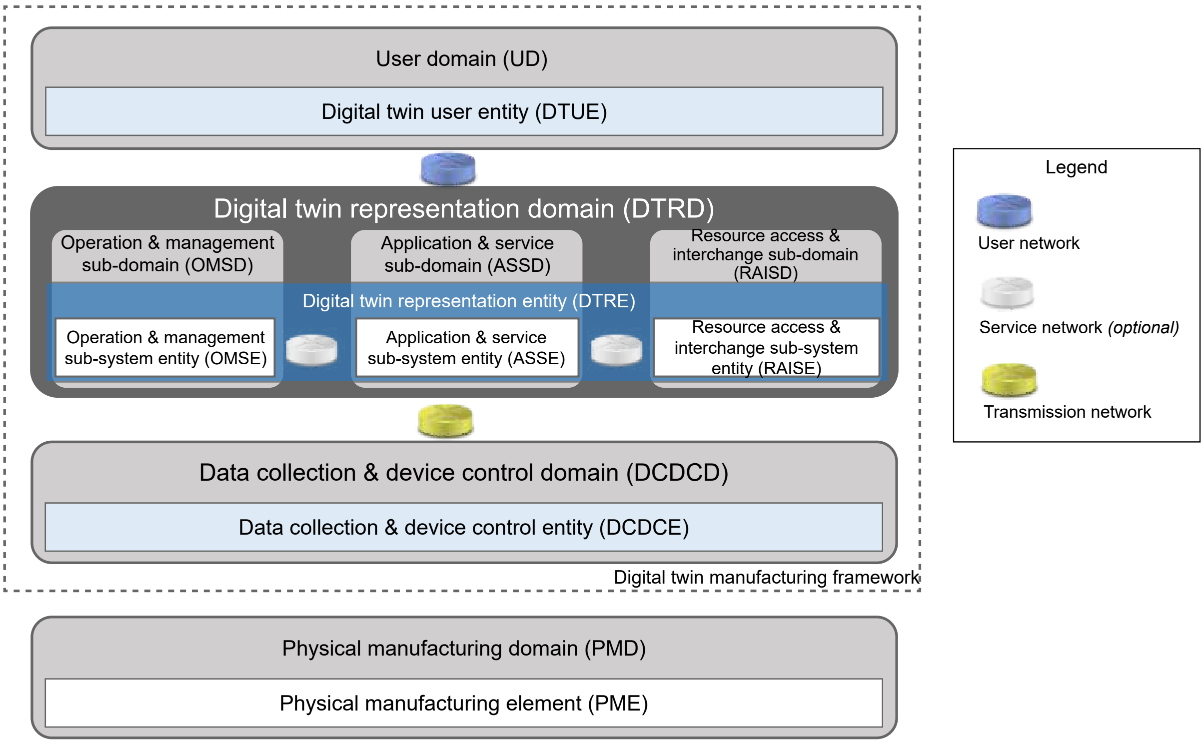

Figure 5-11 | Networking view of digital twin manufacturing reference architecture in ISO 23247-2 [20]

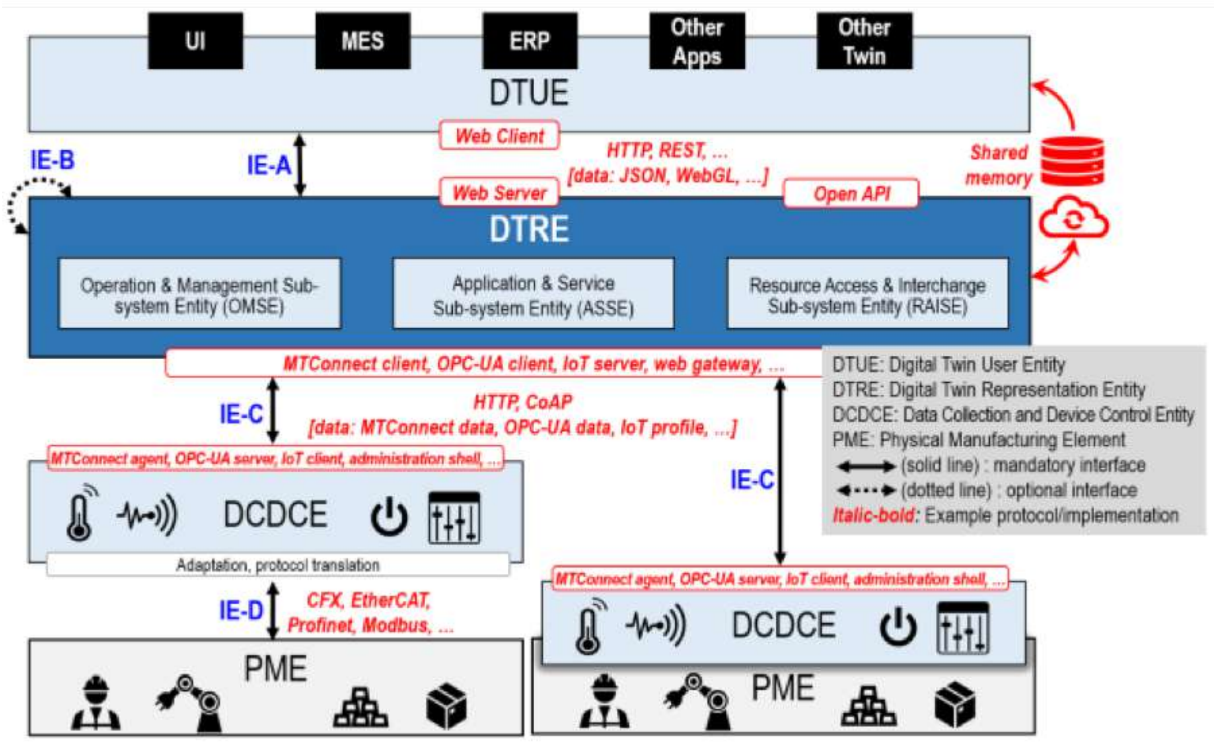

Figure 5-12 | Implementation options for four information exchanges in ISO 23247-4 [22]

For the DTRE and its mapping with various types of source data (see Figure 5-13), the digital twin can be a twinning of application using source data from various applications. It can be a twinning of manufacturing operations using source data from applications, manufacturing elements and sensors/actuators. It can be a twinning of manufacturing elements using source data from manufacturing elements. It can also be a twinning of trends, checklists, etc. It can use data from sensors/actuators.

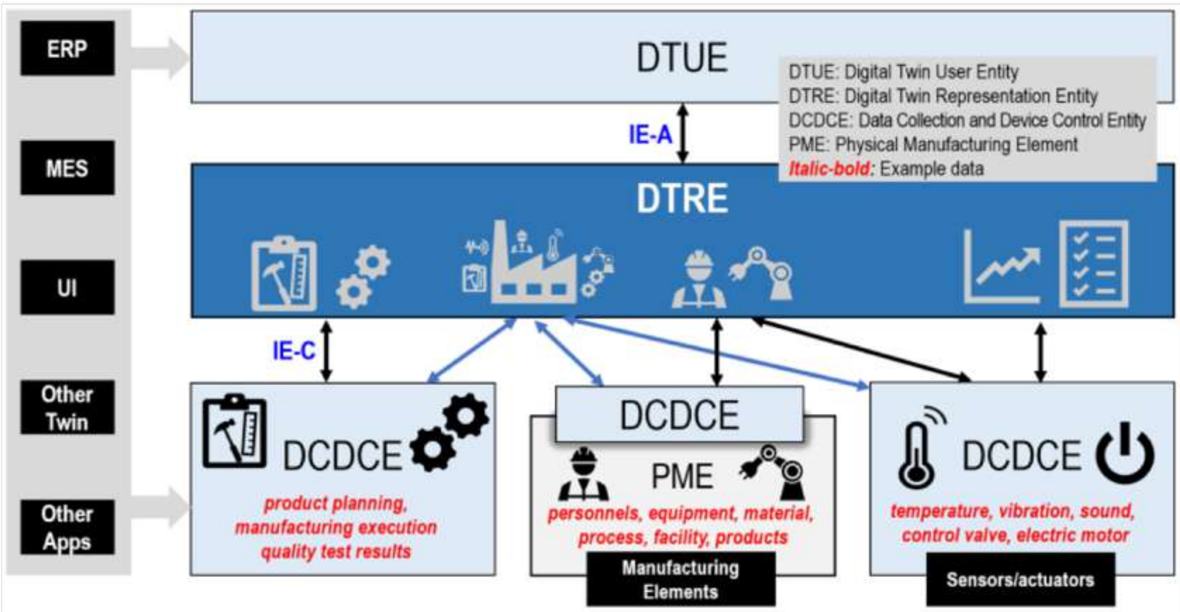

Figure 5-13 | Mapping of digital twin with source data in ISO 23247-4 [22]

5.3 Open digital twin framework for smart city ecosystem

A digital twin is a digital replica of physical assets, processes, people, places, systems and devices that enables better planning and management. It could be a replica of a traffic light, of the water distribution network in a city, or of the city as a whole. It is more than just a model, instead it is "live" software that is tightly linked to the physical reality through near-real-time data via the IoT. In fact, model, data and software are three key factors for digital twin system development.

Built on top of the standard city information model, the city digital twin is cloud native software that represents the physical city across its life cycle, using near-real-time data to enable understanding, learning and reasoning. This pairing of the digital and physical worlds allows analysis of data and monitoring of systems to head off problems before they even occur, prevent downtime, develop new opportunities, and even plan for the future by using simulations. With a digital twin of the city, the complexity and uncertainty of urban planning, design, construction, management and service can be solved through simulation, monitoring, diagnosis, prediction and control in the digital city.

However, there are still many challenges to implementing a digital twin-based smart city. The main problem is the nature of vertical city management. This means that data about different areas of city life are collected separately in different and often incompatible formats by different city agencies, which are often already developing their own digital twins, using proprietary software and data models. This undermines any attempt to use digital twins to manage the city as a whole.

Imagine a major fire breaks out in the city. To deal with it, it is necessary to know where exactly the fire is located, how extensive it is and how fast it is spreading; where people are present in the area and what their escape routes are; how to deal with hazards such as gas pipes or dangerous chemicals; what is the best route for fire engines, given current congestion on the road network; what likely injuries there might be to human life, etc. It is also necessary to provide near-real-time information to all the different agencies that are dealing with the fire so that they can adjust their activity accordingly. To address a challenge like this, the digital twin of the city requires an open platform to support co-construction, co-sharing and co-governance.

In addition to providing efficient infrastructure and connectivity services, telco operators can take the step of jointly empowering and coordinating the development of digital twin applications, along with partners in the smart city *ecosystem*. As the digital twin platform is becoming the core of new smart city architecture, the aim is to build an Open City Digital Twin DevOps Platform to enable the agile development of standard digital twin services by all sectors, such as the spatial twin from GIS vendor, vehicle twin from automaker, buildings twin from real estate and so on. This platform will become a virtual meeting point for multi-stakeholder groups within the smart city and thus augment co-development and collaboration among stakeholders (see Figure 5-14). As a result, the smart city operator could leverage these various digital twin services to orchestrate the digital thread to support any of the use case scenarios.

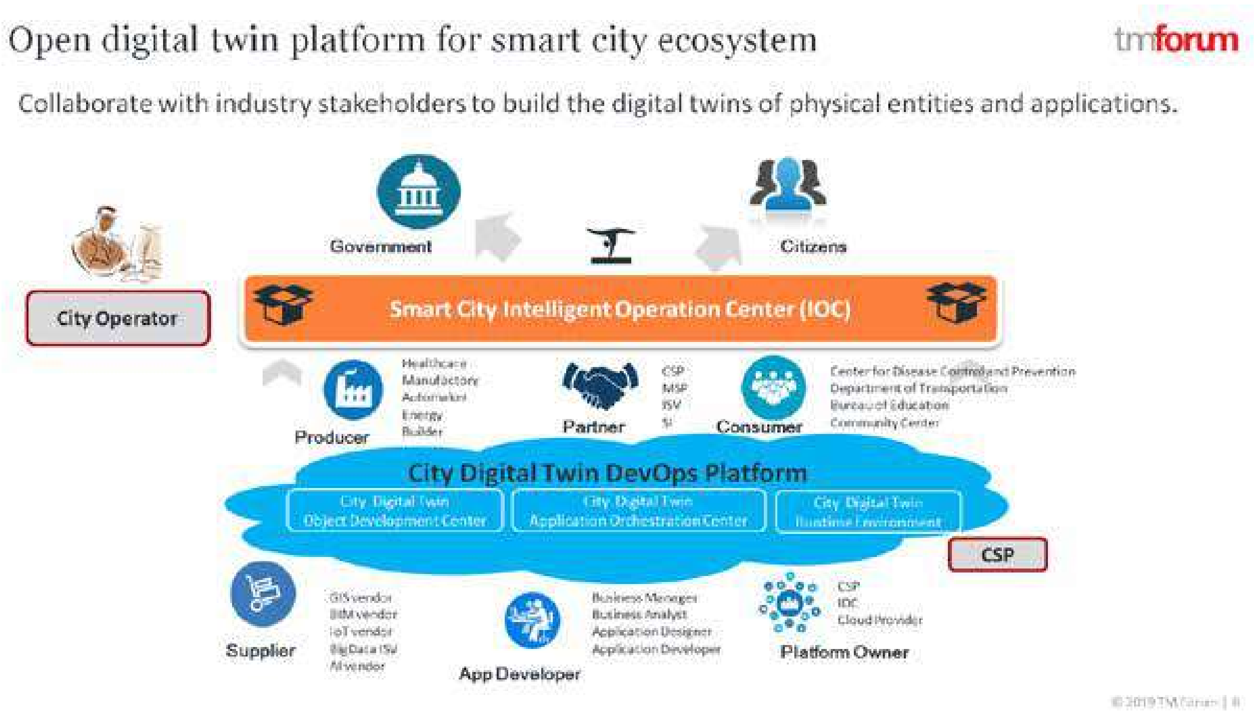

Figure 5-14 | Stakeholders in building the digital twins of physical entities and applications

This platform will realize the interconnection and perception of everything and everyone from different verticals based on a standard model. It must then break the data islands and realize data intelligence through data circulation and sharing cross domain. Finally, it needs to realize smart digital operations quickly and effectively through standardized interoperability technology when facing diverse scenes in the life cycle of the city.

On top of a shared technical platform that provides a common software toolkit such as AR/VR and IoT, and a trusted data platform that builds against CIM, the Open City Digital Twin DevOps Platform has implemented three sub-systems:

1) The development centre for city digital twins: this connects with a large number of organizations and individuals who will develop the specific digital twins from their respective industry field.
2) The orchestration centre for specific use scenario: this is a low-code platform to enable developers assembling the instances of the city digital twin together to define the workflow using drag-and-drop style.
3) The distributed runtime system: this is the operating system to manage each digital thread that drives the instance of the city digital twin to accomplish its tasks in near-real-time.

As one typical use case that requires end-to-end service level agreements from telco operators, network assurance for major sports events is a significant challenge due to the diversity of sports venues and the need for emergency plans to be prepared, for example for the long-distance races or alpine skiing. A specific example involved leveraging the city digital twin to ensure the network service level agreement for the Asian Games during an emergency. Different stakeholders quickly created digital twins for stadiums, buildings, roads, vehicles, people and the network base, and then the telco operator could easily figure out the potential network issues through simulations in different emergency situations even before the opening of the games. Similarly, public security and healthcare departments can also create their own digital thread to manage the emergency situations for which they are responsible.

This Open City Digital Twin DevOps Platform is opening up the opportunity for communications service roviders to march into the field of smart cities and begin to take on a leadership role as city operators.

5.4 Scoping out standards requirements: an example of city information modelling

Scoping out user requirements is important for standards work. User requirements refers to:

a) user-system interaction requirements for achieving intended outcomes (including requirements for system outputs and their attributes); and
b) use-related quality requirements that specify the quality criteria associated with the outcomes of users interacting with the interactive system and that can be used as criteria for system acceptance [26].

The concept of use case modelling was introduced as a software development approach [27]. It is also an important technique/section for standards development.

- It is an efficient way to capture and describe the functional requirements of a system, such as a software system.
- It is an effective tool to facilitate the communication between stakeholders in development projects.
- It supports the development process and promotes a good understanding of the requirements among the stakeholders.

IEC 62559, the standards series relating to use case methodology, establishes technical support for generating and collecting use cases. Specifically, IEC TR 62559-1 [28] provides the basis for a common use case management repository, in order to gather use cases within IEC on a common collaborative platform and to organize a harmonization of use cases in order to provide broadly accepted generic use cases as a basis for the further standardization work. It describes processes and provides basics for the use case approach. IEC 62559-2 [29] defines the structure of a use case template, an actor list and a list for requirements. IEC 62559-3 [30] defines the required core concepts and their serialization into the XML syntactic format of a use case template, an actor list and a list for detailed requirements. IEC SRD 62559-4 [31] gathers recommendations around the application of the use case approach for project-specific developments in a broader sense, whereas Parts 1 to 3 concentrate on the application within standardization, the use case template and the management of an IEC use case repository.

IEC Systems Reference Deliverable (SRD) 63273, *Use case collection and analysis: city information modelling for smart cities*, which was launched in November 2019, is the first known international standards project focused on CIM. In this project, CIM is defined as the development of digital representations of a city made up of large quantities of geo-located data, often including near-real-time data, which enable better city planning and management.

IEC SRD 63273 aims to scope out the requirements of CIM standards by collecting and analyzing multiple use cases, specifically including electrotechnical aspects. This project aims to:

a) identify key stakeholders, develop user stories, and clarify the market relationship among these stakeholders;

b) collect and analyze use cases of CIM, specifically electrotechnical aspects; and

c) use these to scope out the requirements for CIM standards and provide recommendations to IEC regarding planning and management of electrotechnical aspects.

The IEC CIM SRD adopted a multi-step approach to generate and collect the use cases of CIM (see Figure 5-15).

STEP 1 – High level system analysis: this initial step is to generate the list of application areas of city information modelling for domain analysis and preparation for the user story and use case collection.

STEP 2 – User story: this step aims to develop a list of significant user stories based on the corresponding application scenario.

STEP 3 – Use case: this step aims to develop a list of use cases based on the corresponding application scenario and user stories. One user story in Step 2 can be extended to develop one or more use cases.

STEP 4 – CIM use case database and integrative analysis: this step is to establish the CIM use case database and conduct integrative analysis, which includes the analysis of the architecture and standards.

STEP 5 – CIM standard gap and requirement analysis: this step is to use the common requirements to scope out a family of CIM standards and indicate the CIM standard gaps.

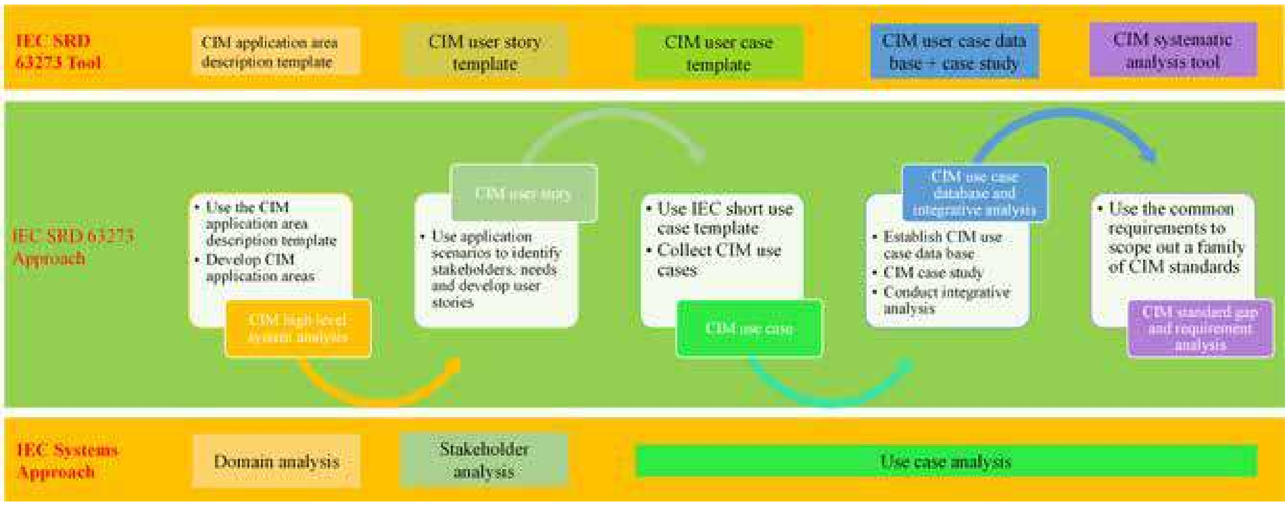

Figure 5-15 | CIM use case collection and analysis in IEC SRD 63273

The template for collection of the CIM use cases was adapted from the IEC short version of the use case [29]. The sections in the short use case template for the IEC CIM SRD include name of use case, date, author(s) (names, institutions, and emails), narrative, and actors.

As of the report publication, the following CIM use cases have been collected:

- New town planning
- Dimensional visualization of property and land administration
- Construction approval management
- Project management during construction
- Real estate registration management
- City management using city brain
- Heritage preservation and revitalization
- Transportation infrastructure planning
- Traffic management
- Water management
- Smart census project

The following CIM use cases are in the process of being collected:

- Urban climate and air quality
- Underground network management
- Disaster and emergency management

The following CIM use cases still require experts to lead the work:

- Virtual hand-over and commissioning
- Disaster and emergency management
- Urban waste management
- Electrical supply
- Oil and gas
- Telecoms
- Renewable energy planning and management
- Commercial property management
- Urban logistics
- Management of drones/unmanned aerial vehicles

More work will be conducted in IEC SRD 63273 on establishing the database with which to conduct a systematic analysis to scope out the requirements of standards for CIM.

5.5 Synthesis

Four presentations on standards work relevant to CIM and UDT were given. The first presentation covered the standards activities undertaken by BSI to develop the UK *Digital Twins for the Built Environment Standards Roadmap – 202*1 [18]. This involved a standard landscaping qualitative analysis to identify priority areas for further standardization. The roadmap and recommendations were supported by UK stakeholders, with a preference to prioritize the development of a standard overview and general principles of digital twins for the built environment. BSI is progressing this work and anticipates that the remaining roadmap recommendations relating to digital readiness, process modelling, interoperability and holistic asset management will be progressed in the near future.

The second presentation covered a digital twin reference architecture demonstrated using a smart manufacturing example. An outline of standards activities across several technical committees was covered, including the work in ISO/IEC JTC 1/SC 41/WG 6 to build general digital twin tools to support different verticals. In ISO/TC 184/SC 4/WG 15, the standards under development are ISO 23247, which focuses on the digital twin manufacturing framework, and ISO/TR 24464 [23], in which the visualization elements of digital twins are analyzed. The remainder of the presentation centred on the development of ISO 23247, which is based on the methodology of ISO/IEC/IEEE 42010:2011 [24].

The third presentation centred on an open digital twin framework for smart city ecosystems, noting that to develop a digital twin system, there are three key factors to be considered: the model, data and software. The main challenge is the nature of vertical city management. This means that data about different areas of city life are collected separately in different and often incompatible formats by different city agencies, which may have their own digital twins using proprietary software and data models. This undermines any attempt to use digital twins to manage the city as a whole. One way to address this challenge is to develop an open platform to support co-construction, co-sharing, and co-governance. There are plans to build such an Open City Digital Twin DevOps Platform to enable the agile development of standard digital twin services by all sectors. This platform will become a virtual meeting point for multi-stakeholder groups within the smart city, and thus encourage co-development and collaboration among stakeholders.

The last presentation covered the scoping of standards requirements for CIM by use cases collection and analysis. IEC SRD 63273, *Use case collection and analysis: city information modeling for smart cities*, launched in November 2019, is the first known city information modelling-focused international standards work. The IEC CIM SRD uses a multi-step approach to generate, collect and analyze CIM use cases. So far, 11 high level use cases have been collected, three are in process, with 10 remaining use cases to be collected requiring experts to lead the work.

Section 6

Differences and overlaps between city information modelling and urban digital twins

6.1 Beginnings

The early stages of theory and research show differences in CIM and UDT. CIM starts from the perspective of the whole city and solutions affecting the city as a whole. CIM can be seen to show a preference for the model, tooling and technologies, whereas UDT focus on the transformation of the physical into the virtual world, and the reactions and simulations that occur between the virtual and physical.

CIM has arisen from BIM as foundational data in the modelling and development of city data management. It is a centralized platform of coordinated city management activities, comprised of various data sources based on uniform standards feeding into a common environment of interactions and the objects that surround them. The platform provides unified services for smart cities based on a unified spatial base map. City information modelling starts from the perspective of the whole city and how the CIM model can look at city-based problems and how to solve them. CIM moves in the direction from the regional macro city model to the micro relationship level. It is about the coordination of a city utilizing the multitudes of urban data sources to build insight and management practices that harmonize operations and activities.

The digital twin traces its origins to product development and discrete simulations of physical objects. It emerged from manufacturing and single asset prototyping such as those conducted by NASA and Formula One racing cars. These digital twins facilitated rapid prototyping and testing, and this groundwork formed the initial modelling concepts.

With the development of digital twin object components, a question needed to be asked as to how this model then interacted with the digital thread context. That relationship also requires modelling, for example modelling a digital twin of a motor vehicle onto the digital twin of the racetrack. It is this expansion of the modelling environment for the purposes of the relationship contextualization that created the move towards UDT. Moving outside of an isolated digital twin object, an examination can be conducted on how an object bears relevance to the digital twinning of the environment in which it operates, and the impact and influences of the contextual environment on the object.

UDT can be seen emerging from this smaller product and component viewpoint to the larger contextual environment, whereas the city information model emerging from BIM employed a built environment context at an early stage of its theoretical developments. This has led to a stronger focus on the city-wide management aspect of the development of larger scale integrated systems and architectures.

UDT can be seen in their composition as discrete ecosystems that can be linked, this reflecting back to the origins of technology within product and facility twinning. They act as distributed ecosystems that are looking to be interconnected and interoperable. UDT are about the federation and ecosystems of twins being functional through linking, not through the provision of one centralized platform. The interfaces involved have linked and shared data sources that can interact with separate ecosystems.

6.2 Convergence

If a dataset is to be maintained from a system-thinking view, a UDT cannot be developed without using CIM. The CIM can exist as a starting point on the basis of which the maintenance system of a digital twin can then perform. The city information model creates the city elements that need to be observed in the UDT, such as buildings and roads: essentially the infrastructure of the city.

Appropriate levels of synchronization for the requirements of management and maintenance of an asset are necessary for UDT. Without the authoritative underlying data source of a city information model, the digital twin synchronization would bear little relevance to synchronizing a city component. It is the CIM that supports the proper data management and modelling into the UDT.

A model of a bridge can be developed using building information modelling to support the design and construction of that bridge. If sensors are incorporated into the bridge, once the bridge is built, a subset of the digital model that was used to design and build it can be developed into a model to help monitor its condition for maintenance purposes. The model can then potentially be further developed to monitor its operation in order to show, for instance, how much traffic is using it. Thus, building information modelling is evolving from merely being used at the construction stage to providing an important role in the ongoing maintenance and operation of buildings and structures. In the same way, CIM is evolving toward performing an ongoing role in the management of city assets by linking the models with data coming from sensors and other IoT devices.

CIM, therefore, not only includes various types of static data, such as planning data, environmental data and data relating to building regulations, but also includes dynamic and near-real-time data from sensor devices. Near-real-time multi-source data is more conducive to urban evaluation, prediction, and monitoring. It also has gone through the digital transformation from the real world to the virtual world and is able, in turn, to affect the physical world.

The key difference between CIM and UDT lies in the starting point. UDT brings the experience from industry of using digital models not only to predict, but also to monitor and manage performance. This is particularly strong when it comes to modelling the interaction of different digital twins together, especially the interaction of digital twins of populations with digital twins of the environment. From the UDT perspective, CIM simply provides the model of the built environment, within which various scenarios can be modelled and monitored. On the other hand, proponents of CIM see the value of the model of the city they can generate, not only to plan but also to help with the ongoing management of the city. Because of this, they are continuing to develop more and more sophisticated ways of linking CIM with IoT data and using big data and AI to provide managers with the information they need to manage the city.

It is no surprise, therefore, that CIM and UDT appear to be converging at the level of the system and IT architecture, in addition to the level of what they are both attempting to achieve within the city and urban environment: that of maintenance, monitoring and modelling. The differences have decreased, and the overlaps have increased as time has passed and each has continued to develop. Both CIM and UDT are reliant on developing technologies, such as IoT and big data. They both clearly have a common objective, that of making the city better and smarter.

6.3 Synthesis

It appears that through the early stages of theory and development CIM and UDT have emerged from the attempt to solve different problems within the urban environment.

CIM has taken on an enterprise architecture approach to modelling the city, and the digital twin has emerged from domain-specific single-object and system prototyping, such as that found in products and manufacturing.

The gap between CIM and UDT is reducing, as the whole city vision and domain-specific vision begin to converge. The macro of CIM and the micro of digital twins are converging and the space between them is where the work is to be done. The city information model looks to become stronger in managing the dynamic aspects of city functions and digital twins are now considering the needs of more holistic city functions, as well as urban-based problems and solutions.

The overlaps seen within CIM and UDT include the desire to comprehensibly model city infrastructure digitally, to trace the physical object in the city, to monitor and to simulate the object in virtual spaces. Both CIM and UDT include city and domain-specific use cases, integration of big data, AI, IoT and BIM, and they both progress through physical to digital transformation activities and monitor the interaction between the digital and physical worlds. Both CIM and UDT aim to create better and smarter cities.

What we see now is a convergence and a narrowing of the gap between CIM and UDT, which allows for both approaches to learn from each other moving forward. Without an appropriate authoritative model within CIM the twinning brought about by a UDT cannot continue in its capability of monitoring real world objects and processes in a digital realm. Whilst the macro is a high-level consideration found in the origins of CIM, the dynamic movement and change within city assets and systems is increasingly important. So as CIM focuses down into the specific industries and entities within the city and their interaction with each other, UDT continue to focus outwards from their domain-specific objects and operations.

Section 7

Conclusions and recommendations

7.1 General

7.1.1 What has been learned from the forum

Both city information modelling (CIM) and urban digital twins (UDT) have the same aims of enabling better urban planning and city management by using data and smart technologies. The customers of such intelligent technology solutions include, but are not limited to, local government, the public, businesses and private investors.

Both CIM and UDT involve many different layers of city data. Collecting the right data, setting standards for data, and sharing the data securely become some of the important challenges for using CIM and UDT in smart city planning and management. There are also different levels of data: micro, meso, and macro, which are needed for integration, visualization and simulation by CIM and UDT.

Rather than consisting simply of specific tools, software and data, both CIM and UDT are practices of using technology in an interoperable and interactive way to make decisions and plan for the smart city. Good communications and close collaboration between all stakeholders – urban planners, SDOs, researchers, software developers and decision-makers – are needed to achieve the goal of delivering smart cities by using intelligent tools.

7.1.2 Gap between reality and ideal goal / Gap between the current state of development and what is needed in the future

Both CIM and UDT are still at an early stage and face common challenges and questions for their future development, which include data silos, the usability and usefulness of applications for stakeholders, integration/interoperability, openness, regulation and the development of necessary skills and education.

Models, data and software are important components for both CIM and UDT and both need to meet the challenges of data collection, data management and security sharing. Unified standards are still lacking to help manage these challenges. Specifically, standards are needed that address the following issues:

- How can the different disciplines be aligned, and technologies be linked, in CIM and UDT?
- What are the standards for convergence of different types of data in CIM and UDT?
- How can the public be involved in the development and usability of CIM and UDT when used for consultation and to support citizens in managing their lives in the city?
- How can CIM and UDT support the communication between humans and virtual environments?

7.2 Standards and other developments required

Based on the presentation and discussion, the following standards work should be prioritized:

An integrated reference architecture of CIM and UDT needs to be developed. It is suggested that IEC SyC Smart Cities, ISO/IEC JTC 1/SC 41: Internet of things and digital twin, Open Geospatial Consortium, ISO/TC 211: Geographic information/Geomatics, and other relevant standards organizations prioritize working together to develop this.

Enabling the connection of different types of city data needed by CIM and/or UDT should be one of the focuses for standards work. Therefore, it is recommended that IEC SyC Smart Cities undertake the work of use case collection and analysis for identifying the requirements of connecting different types of data for the specific application areas/scenarios. Standards for uniform data formats for CIM and UDT should be considered in the future work. For example, it needs to be determined how to extend Industry Foundation Classes (IFC) and CityGML data models to meet the needs of CIM/UDT.

A full set of use cases of CIM and UDT for different application areas/scenarios is needed to identify the requirement of standards for CIM and UDT. IEC SRD 63273 is collecting and analyzing use cases of CIM. It is recommended that a similar piece of work should be undertaken to collect use cases for UDT, which will also address **the social systems**, including mobility, health, disaster and emergency management, etc.

Standards for CIM and UDT platforms are needed. These will include functions, interfaces, resource models, services and devices to support effective sharing and exchanging information.

Collaborative standards work among the different SDOs is vital to develop effective standards for CIM and UDT. IEC SyC Smart Cities is developing IEC SRD 63273, *Use case collection and analysis: city information modelling for smart cities*. ISO/IEC JTC 1/SC 41: Internet of things and digital twin, has begun generic standards work related to digital twins compatible with many different application domains, including manufacturing, maritime and underwater and the built environment. OGC is working on smart city-relevant standards with a particular emphasis on CityGML, API Features, GeoVolumes API and SensorThings API. So, a good start would be for IEC SyC Smart Cities, ISO/IEC JTC 1/SC 41, OGC, and other relevant SDOs to work collaboratively to identify the requirements for, and then help develop, international standards for CIM and UDT.

In addition to the above standards work, recommendations for research and practice coming out of the workshop and this report include:

- The organizing committee should work with the speakers and other interested parties to develop collaborative research projects to further clarify the theories/concepts of CIM and UDT.
- Urban planners are the natural leaders for implementing CIM and UDT as the convergence of multiple trends. It is recommended that the relevant professional bodies and national government agencies develop practical guidance and training for them in this area.
- More widely, it is recommended that universities and professional organizations build national and international education and training programmes for training the next generation of experts for applying CIM and UDT for smart cities.
- It is also recommended that relevant professional organizations and national government agencies generate interest and demand for CIM and UDT, and foster collaboration by aligning goals of all stakeholders to a higher order purpose and common goal.

- The UK, Australia, and the US have developed national digital twin hubs. It is recommended that such national, regional and international hubs be developed in more countries/areas to bring together industry, government, academic institutions and NGOs to further development, research and practice, and that these hubs should make CIM and UDT a key focus.

Given the value gained from the workshop on which this report was based, the organizing committee intends to hold further workshops to continue to support the conversation between CIM and UDT.

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