Institution of Civil Engineers

Publishing

Digital Twins in the Built Environment

Fundamentals, principles and applications

Qiuchen Lu, Xiang Xie, Ajith Kumar Parlikad, Jennifer Schooling and Michael Pitt

ice Publishing

Lu, Xie, Parlikad, Schooling and Pitt
ISBN 978-0-7277-6580-2
https://doi.org/10.1680/dtbe.65802.001

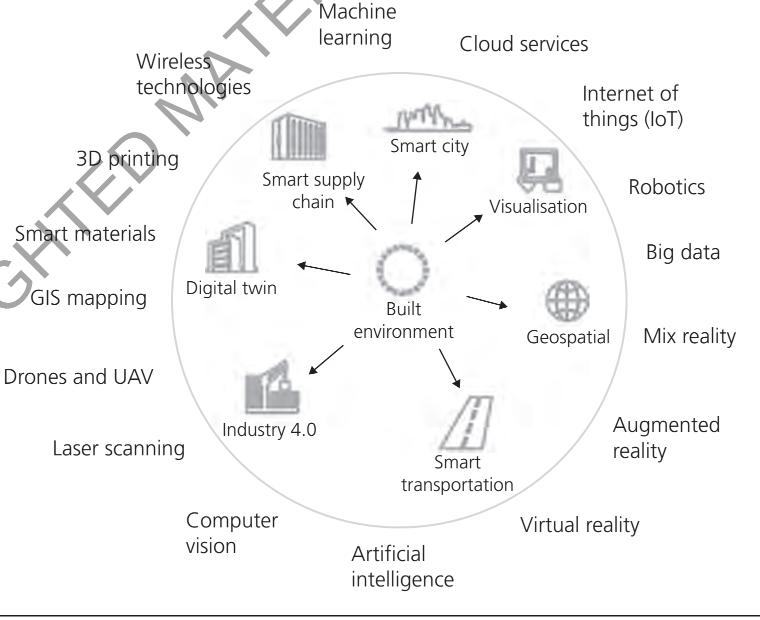
Chapter 1
Introduction

1. Scope of this book

The digital age is approaching. Various digital concepts and technologies are transforming our built environment, such as big data, robotics, laser scanning and digital twins (as shown in Figure 1.1).

A digital twin (DT) refers to a digital replica of physical assets, processes and systems. Digital twins integrate artificial intelligence, machine learning and data analytics to create living digital models that are able to learn and update from a number of data sources, and to represent and predict the current and future condition of their physical counterparts. Digital twins align well with other related emerging paradigms, such as cyberphysical systems and Industry 4.0, and it is predicted that half of the large industrial companies will use digital twins by 2021, resulting in those organisations gaining a 10% improvement in effectiveness (Gartner, 2017). Moreover, from the perspective of research, the number of publications (with 'digital twin' in the title) has increased significantly, to more than 1200 since 2018, based on keyword search results.

Figure 1.1 Brief summary of digital concepts



ICE Publishing

Lu, Xie, Parlikad, Schooling and Pitt
ISBN 978-0-7277-6580-2
https://doi.org/10.1680/dtbe.65802.055

Chapter 4
System architecture of digital twins

This chapter will introduce a multi-tier digital architecture designed for the establishment of digital twins in the architecture, engineering and construction (AEC) sector. During this process, the Gemini Principles highlight a nice set of key principles or values that digital twins should adhere to and guide the direction of the digitalisation journey of buildings, cities and the wider built environment. In particular, the functionalities and implementations of each layer are briefly described and the benefits of the proposed architecture are summarised.

1. Introduction

Digital twins realise a means to twinning digital modes and analytical simulation engines with real-world data, helping organisations to maximise the value of data and contributing to beneficial synergies across the wider built environment. Accordingly, digital twins can support various applications, such as facility management, security and health management and energy management, to name a few. However, it is notable that each application may have unique data requirements that need to be catered for. This is problematic, considering that data come from a wide diversity of source systems with different intentions of use, and the acquired data do not necessarily match the requirements of all those applications. Dealing with these conflicts and repurposing data from the source systems poses a great challenge (Woodall, 2017). Aiming at managing all data in a unified and flexible manner, a specific architecture for digital twin development needs to be defined for the architecture, engineering and construction (AEC) and facilities management (FM) sectors. To standardise the implementation of digital twins, this chapter develops a multi-tier common architecture using a unified, hierarchical and extensible approach, which should be applicable for various types of infrastructure across different scales, from *assets* and *buildings* to *cities*. Based on the proposed architecture, data are gathered, aggregated, reasoned, analysed and ultimately used to deliver a significant range of services and applications.

2. Design of multi-tier architecture

Borrowing the basic ideas behind the Open System Interconnect (OSI) reference model, various researchers have proposed multi-tier architectures to support heterogeneous application environments, with the aim of making data accessible, aggregated, useable, exploitable, and so on. This includes cyberphysical systems (CPSs), the internet of things (IoT) platform and smart cities and big data platforms, in which multi-tier architectures composed of three to five layers are presented. Multi-tier architecture, also known as onion architecture, is defined as a set of layers (Terrazas *et al.*, 2019). A layer, in this context, is a logical division that aggregates software components by functionality without taking the physical location into account. Systematically, this architecture can be seen as enclosed layers arranged on top of each other. It means that software components within one layer share common functionality and are independent of other components located in other layers. Also, each layer is restricted to communicate with the upstream and downstream layers only, and is allowed to invoke functionality from the lower adjacent layer only. Therefore, based on the previous works, multi-tier architecture brings a few benefits. First, it enables independent implementations of every single layer as a coherent whole without knowing much about the other layers. Second, it facilitates the substitution of

Lu, Xie, Parlikad, Schooling and Pitt
ISBN 978-0-7277-6580-2
https://doi.org/10.1680/dtbe.65802.255

Chapter 11
Case studies: digital twin implementations at the system level

Systems are the fundamental units that deliver functional, environmentally responsible and maintainable, easy to operate services in a building. This chapter will illustrate the implementation of digital twins at the system level, demonstrating the data representation, data analysis and decision-making capabilities that the digital twin possesses. Based on the multilayer digital architecture proposed in this book, two real-life case studies are presented, focusing respectively on anomaly detection for building asset monitoring and fine-grained building energy analysis.

1. Introduction

People spend almost 90% of their time indoors. Buildings are the places where people live, learn, eat, sleep and often work and play. To guarantee the well-being and productivity of human beings, buildings encapsulate diverse systems to make them comfortable, functional, efficient and safe (Wong *et al.*, 2008a). These systems can include fire safety, heating, ventilation and air conditioning (HVAC), lighting and plumbing. Taking advantage of the fourth industrial revolution, which is blurring the lines between the physical, digital and biological spheres (Schwab, 2016), a vast ecosystem of interconnected and dynamic interaction between human beings and the built environment is gaining momentum (Ross and Maynard, 2021). This accelerates the digital transformation of buildings and their systems, from conventional and programmatic to sentient and intelligent. Plageras *et al.* (2018) surveyed internet of things (IoT), cloud computing, big data and sensor technologies with the aim of collecting and managing heterogeneous building data. Data come in many forms, including static, dynamic, functional, behavioural, environmental, sensor-based and listings in handbooks, manuals, and so on. Built on the ubiquitous sensing capability and computer power at our disposal, building systems are endowed with intelligence and wisdom, reflected in their autonomy, observability and controllability for complicated dynamics, human–machine interaction and bio-inspired behaviour (Wong *et al.*, 2008b). Building intelligence leads to not only enhanced operational effectiveness and energy efficiency, improved occupant comfort and productivity, but also increased safety and reliability of buildings (Love and Matthews, 2019).

As the carrier of the building intelligence, a digital twin is the virtual counterpart of an asset (in this context, of the building, system and component); it digitally mirrors, predicts and manages the asset's behaviour along its lifecycle (Dietz and Pernul, 2020). Of course, from a practical standpoint, a digital twin should not be a singular model of an entire building, but rather a consolidation of several, previously discontiguous localised system digital twins that are networked in a system-of-systems manner. These assets and a suite of underlying digital twins work collaboratively to achieve a friendly indoor environment and ultimately promote maximum profitability for the business. Seghezzi *et al.* (2021) defined an occupancy-oriented digital twin to monitor actual occupancy levels in building spaces using IoT camera-based sensors, in order to guide the optimisation of space utilisation, as well as customised cleaning activities and contracts. Lu *et al.* (2020) implemented a digital twin-enabled asset monitoring solution that continuously identified suspicious anomalies of critical assets, such as centrifugal pumps.

Lu, Xie, Parlikad, Schooling and Pitt
ISBN 978-0-7277-6580-2
https://doi.org/10.1680/dtbe.65802.291

Chapter 12
Case studies: digital twin implementations at the building level

Following the implementation of digital twins at the system level, this chapter introduces the usage of the proposed digital twin architecture at the building level. A building is a collection of diverse systems that provide various services to its occupants. This chapter gives an overview of consistent realisation techniques across different systems used in the building digital twin, particularly in terms of data acquisition, transmission and management. Real-life buildings are used to showcase the implementation process and the lessons learnt from the cases.

1. Introduction

As digital replicas of physical buildings, digital twins at the building level are widely promoted as a potential solution to collect and digest heterogeneous data from diverse building systems and track the real-world behaviour of these buildings (Boje *et al.*, 2020; Khajavi *et al.*, 2019; Lu *et al.*, 2020). Based on the digital twin architecture proposed in this book, a case study is presented with the purpose of establishing digital twin prototypes for the Alan Reece Building located in the West Cambridge site of the University of Cambridge. Although similar digital twin system architectures can be adopted – in fact, the digital technologies and models adopted, as well as the applications developed, could be manifold, as the selection of these depends on the realistic situation and stakeholder requirements of particular cases – this chapter aims to provide an overview of the whole journey of developing digital twins at the building scale, elaborating some technical details and sharing lessons learnt and challenges involved in real practice.

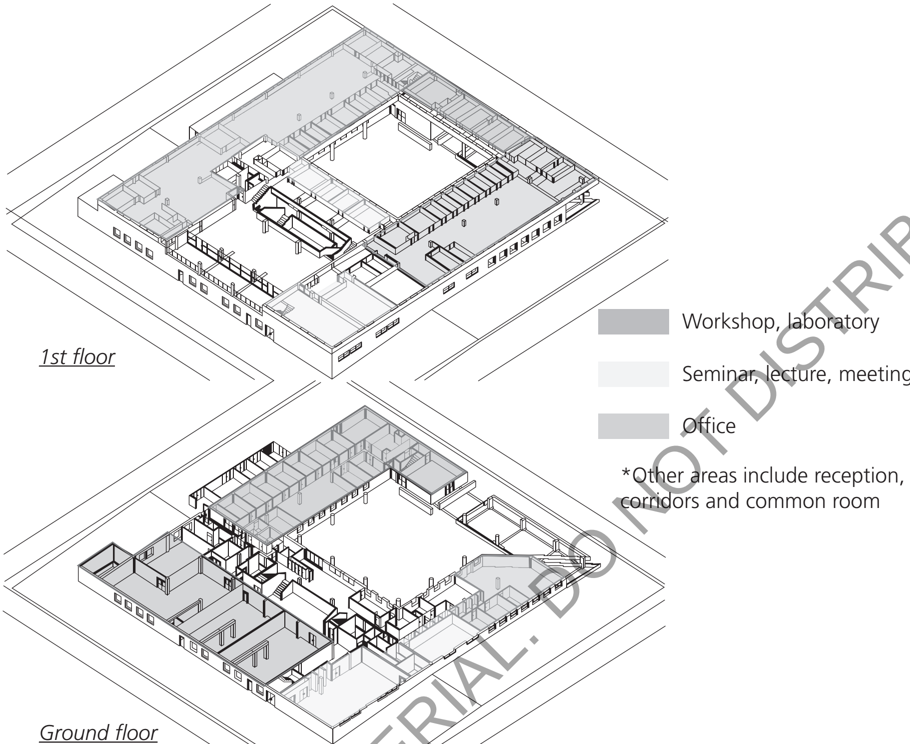
2. Building-level digital twin pilot

The pilot study of the proposed digital twin architecture was conducted in the Alan Reece Building. The Alan Reece Building is the main office block of the Institute for Manufacturing (IfM). The Alan Reece Building, shown in Figure 12.1, is a two-storey structure and covers a comprehensive area of more than 4000 m^2, including teaching, study, office, research and laboratory spaces.

Five critical stakeholder groups were engaged in the development of the building digital twin:

- The university estate management team is responsible for satisfying the O&M requirements for the entire university.
- The university facility management team is responsible for the day-to-day O&M activities for a specific building or location within campus.
- A modelling and data collection company supported the data collection and model development of the digital twin, including unmanned aerial vehicle (UAV) point cloud scanning and localised laser scanning and photogrammetry.
- A consulting company provided project management and collaborative expert support.
- The academic team provided overall leadership in the process and was responsible for the design and implementation of the architecture. Further, the academic team also ensured that the digital twin development architecture and methodology were correctly implemented and was repeatable and extensible.

Figure 12.1 Layout of the Alan Reece Building



Based on the developed system architecture, as discussed in previous chapters, the building digital twin integrated various data resources and realised several applications. The objective of this pilot was to demonstrate how a dynamic digital twin of an existing building can be developed and to explore potential opportunities and challenges.

2.1 Data acquisition layer

Data acquisition from the building and physical built assets forms a basic bottom layer in the proposed system architecture. There are two main data sources in the building digital twin: off-the-shelf sensors, working over a radio frequency of 868 MHz, deployed at distributed locations (Table 12.1) and existing facilities management (FM) systems (Table 12.2), such as the building management system (BMS), asset management system and space management system (SMS). The BMS installed in each building controls, monitors and manages mechanical and electrical systems (e.g., power systems, heat, ventilation and air conditioning (HVAC) systems and security systems). The asset management system is a work-order management system that keeps records of all asset management activities and services conducted on university-owned assets. In this pilot, the Planet asset management system was used for managing built assets, including asset register, preventive maintenance plan and storeroom stock (University of Cambridge, 2021a). The SMS manages room bookings, and provides space utilisation information. MiCAD SMS is a cloud-based publishing system used in this pilot that holds CAD floor plans, building condition records and room booking details for each building in the West Cambridge site (University of Cambridge, 2021b).