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Digital Twin and its implementations in the Civil Engineering Sector

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Abstract

Digital Twin (DT) concept has recently emerged in civil engineering; however, some problems still need to be addressed. First, DT can be easily confused with Building Information Modelling (BIM) and Cyber-Physical Systems (CPS). Second, the constituents of DT applications in this sector are not well-defined. Also, what the DT can bring to the civil engineering industry is still ambiguous. To address these problems, we reviewed 468 articles related to DT, BIM and CPS, proposed a DT definition and its constituents in civil engineering and compared DT with BIM and CPS. Then we reviewed 134 papers related to DT in the civil engineering sector out of 468 papers in detail. We extracted DT research clusters based on the co-occurrence analysis of paper keywords' and the relevant DT constituents. This research helps establish the state-of-the-art of DT in the civil engineering sector and suggests future DT development.

Keywords: Digital Twin, civil engineering, Building Information Modelling, cyber-physical systems, asset management, operations and maintenance, defect detection

Abbreviations: 5C, connection-conversion-cyber-cognition-configuration; 5G, the fifth generation of broadband cellular network technology; AHU, air handling unit; AI, artificial intelligence; AR, augmented reality; BIM, Building Information Modelling; BIM2BEM, BIM to building energy management; BLE, Bluetooth Low Energy; BrIM, Bridge Information Modelling; CAD, computer-aided design; COBie, Construction Operations Building Information Exchange; CPS, cyber-physical system; DNAS, drivers, needs, actions, systems; DT, digital twin; FDD, fault detection and diagnosis; FTA, fault tree analysis; gbXML, Green Building XML; GIS, geographic information system; GNSS, Global Navigation Satellite System; GPS, Global Positioning System; GSM, Global System for Mobile Communications; HVAC, heating, ventilation, and air conditioning; IDM, Information Delivery Manual; IFC, Industry Foundation Classes; IFC4 ADD2, IFC4 – Addendum 2; IMLE, iterative maximum likelihood estimation; IoT, Internet of things; LAN, local area network ; LiDAR, light detection and ranging; MR, mixed Reality; MVD, Model View Definition; NASA, National Aeronautics and Space Administration; NFS, neuro-fuzzy systems; O&M, operation and maintenance; OBiDE, Occupant Behaviour in Dynamic Environments; PDA, personal digital assistant; PHP, prefabrication housing production; QR code, Quick

Response code; RCM, reliability-centered maintenance; RF, radio frequency; RFID, radio-frequency identification; RTLS, real-time location system; SHM, structural health monitoring; SIR, savings-to-investment ratio; UAV, unmanned aerial vehicle; UHF, ultra high frequency; VR, virtual reality; Wlan, wireless LAN; XML, Extensible Markup Language

1 Introduction

The development history of Digital Twin (DT) is relatively brief. It is widely acknowledged that Michael W. Grieves's Product Lifecycle Management model was DT's origin in 2002 [46]. DT applications started emerging with the recent development of the Internet of Things (IoT). Both technologies share the same nature - connecting a physical artefact and its digital counterpart [3]. Researchers from various domains have made various definitions for DT. Grieves and Vickers [46] defined DT as a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. Any information obtained from inspecting a physically manufactured product can be obtained from its DT at its optimum. Tuegel, et al. [111] regarded DT as making high-fidelity digital models and high-fidelity digital environments and loads for aircraft structural simulation and life prediction. NASA defined DT as an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates and fleet history to mirror the life of its corresponding flying twin [42]. Rosen, et al. [95] pointed out that autonomous systems will need access to very realistic models of the current state of the process and their own behaviours in interactions with their environment in the real world, which is typically called DT. Based on the definition of digital model and digital shadow, Kritzinger, et al. [61] proposed that the data flow between an existing physical object and a digital object are fully integrated as a DT. In such a combination, the digital object might also act as a controlling instance of the physical object. A change in the physical object's state directly leads to a change in the digital object's state and vice versa. Tao, et al. [108] proposed that DT has five parts: physical part, virtual part, connection, data, and services.

DT is a fast-evolving technology concept that has many successful use cases across sectors. Applications have expanded to the civil engineering sector, but some research has confused DT with other concepts, such as building information modelling (BIM) and cyber-physical systems (CPS) . The constituents of a DT in the civil engineering sector are not clear [22]. Also, there is an increasing need to understand what DT can bring to the civil engineering industry and how good it can be as DT applications continuously emerge. A systematic review is conducted to address these questions. The objectives of this review are as follows:

1) Distinguish DT from BIM and CPS and propose a new definition for DT.
2) Identify clusters of DT-related research topics in the civil engineering sector.
3) Discuss the current and future development for each of the DT-related research topics.

The research includes a two-step literature review. Section 2 defines the DT and its constituents based on a first-round review; section 3 illustrates the DT applications and research clusters in the civil engineering sector based on a second-round review; section 4 discusses the current and future development of each research cluster illustrated in section 3. Section 5 concludes the research.

2 Definition of DT

The first round of literature review aims to establish a definition of DT and its key components. The review was conducted through the following steps, as shown in Fig. 1.

1) Find relevant research papers
    a) Select target journals: Based on the data in Scimago Journal Rank, first, journals that fit the subject areas of "civil and structural engineering", "building and construction" and "architecture" were chosen; then, the top 50% of journals (Q1 and Q2) in the list were selected as the sources. The ISSN numbers of these journals were used to construct the search query.

   b) Choose keywords: In order to compare research on DT, BIM and CPS, the following terms were used to construct the search query - "DT", "as-is BIM", "existing BIM", "as-is building information modelling", "existing building information modelling", "cyber physical", and "cyber-physical".
   c) A query that combines a) and b) steps output 468 papers in the Scopus database.

2) Analysis of bibliographic data
   a) Keywords and author keywords were extracted from the bibliographic data of the 468 papers. These terms were cleaned up (remove stop words and combine synonyms) to consolidate and increase the keywords' consistency.
   b) After filtering out irrelevant keywords and corresponding papers, we selected 134 papers that discussed DT applications in the civil engineering sector.

3) Establish the DT Definition
   a) After reading the full text of these 134 papers, we established a DT definition and classified these papers into three categories: DT, BIMtoDT and CPStoDT, which referred to papers about DT, papers about BIM but actually about DT, and papers about CPS but actually about DT, respectively.

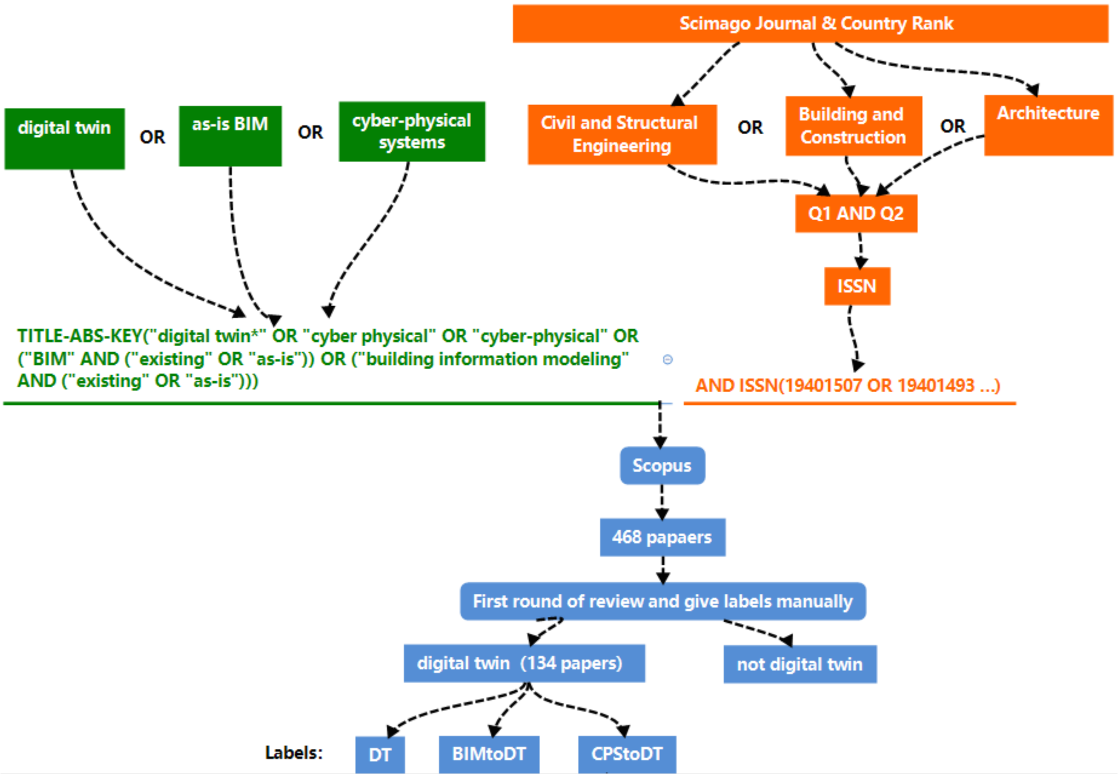


Fig. 1 First-round review process

2.1 DT and its Constituents

Tao, et al. [108] proposed that DT must consist of five parts: physical part, virtual part, connections, data, and services. The physical part is the basis of the virtual part; the virtual part mirrors the physical part in a controlled setup; the connections enable data transfer and control; a DT must provide some services, such as simulation, decision making, monitoring and control of the physical object; and data drives the services to enhance the convenience, reliability, and productivity of the system.

Based on the existing proposed concept, we made some further clarification. First, a DT should use virtual representations to express the physical counterpart [42,46,95,111]. Second, a DT connection requires data transfer from the physical object to the virtual part [61], but feedback is not mandatory. Third, the virtual part can control the physical counterpart [61], but this is not mandatory. Finally, the DT must provide a specific service [108], as shown in Fig. 2.

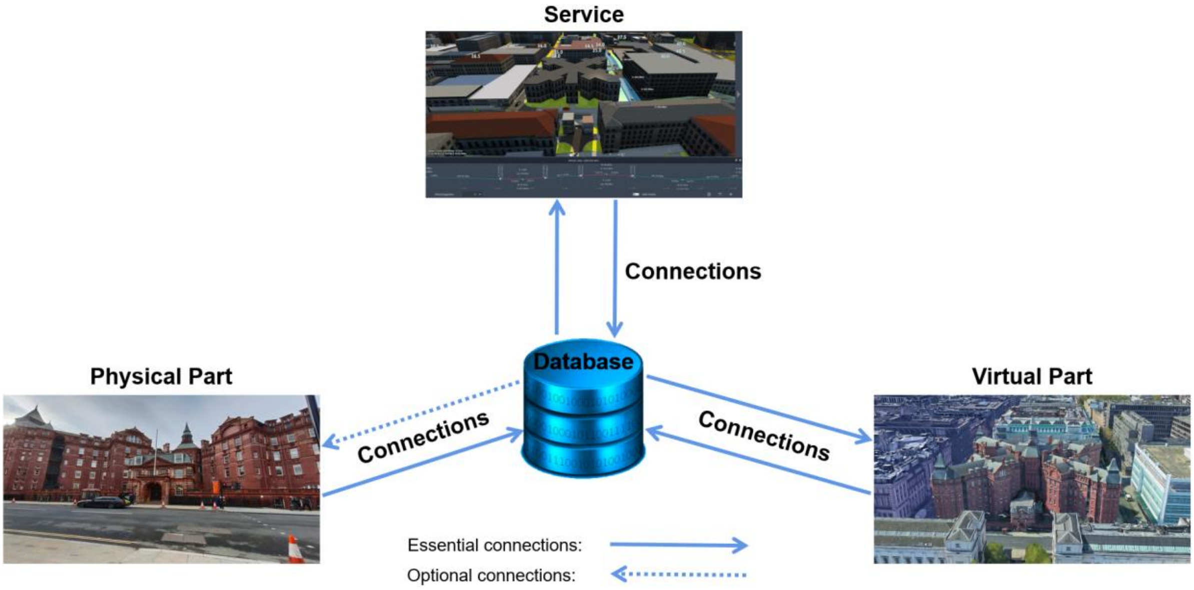


Fig. 2 Five-part structure of DT

2.2 *DT vs BIM and CPS*

A BIM model is a digital representation of a built object's physical and functional characteristics [54]. Some comparisons between DT and BIM should be presented:

1) Both a BIM model and a DT require a virtual model.

2) DT emphasizes the existence of the physical counterpart while a BIM model does not.

3) A BIM model can represent something that does not exist or have not been built. A DT must reflect the physical counterpart's existing state in a timely fashion, while BIM does not necessarily have to.

4) A more similar concept to DT is 'as-is' BIM model. Nevertheless, the former emphasizes connections with the physical part while BIM or 'as-is' BIM do not.

Lee [65] proposed that a CPS is an orchestration of computers and physical systems. Embedded computers monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa. Lee, et al. [66] proposed a 5C architecture of CPS that included the following: 1) a smart connection that can acquire accurate and reliable data from machines and their components; 2) data-to-information conversion that can infer meaningful information; 3) cyber that acts as the central information hub to form the machine's network; 4) cognition that generates thorough knowledge of the monitored system and gives a proper presentation of the acquired knowledge to expert users to support decision making; and 5) a configuration that is the feedback from cyberspace to physical space. Some comparisons between DT and CPS should be presented:

1) DT and CPS both emphasize the existence of physical objects.

2) Both concepts involve data transfer between the physical objects and virtual models in a timely fashion.

3) DT requires a virtual model, while CPS does not have to. In other words, DT focuses on "virtual", while CPS focuses on "cyber".

4) DT must have a twin relationship between a physical entity and its corresponding virtual entities; however, CPS does not have to.

It should be emphasized that the twin relationship refers to that every physical part can find a corresponding virtual part, and similarly, every virtual part can find a corresponding physical part. In the project life cycle, environments, conditions, requirements, physical parts, virtual parts, data, connections, and services can flexibly change. Thus, DTs have to accommodate uncertainties. Though the physical part and the virtual part can change and it is difficult for the virtual part to replicate the physical part 100% accurately, a twin relationship can be found.

The overall differences between DT, BIM and CPS are listed in Table 1. In this table, "O" signifies that the element is optional, while " √ " signifies that the element is compulsory.

Table 1 Differences between DT, BIM and CPS

Elements	BIM model	Digital Twin	Cyber-Physical Systems
Physical part	O	√	√
Virtual model	√	√	O
Connections between physical and virtual models	O	√	√
Twin relationship between the physical part and the virtual model	O	√	O

3 Research Cluster of Applications

In the second round of literature review, we classified the papers and their keywords using labels from the list of DT constituents, i.e., physical parts, virtual parts, connections, data, services, technologies. A paper may have discussed more than one constituent; then, all corresponding labels will be assigned to the paper. Table 2 shows the classification results. The numbers after each keyword signify the number of papers that use the corresponding keyword.

Table 2 Keywords and the number of papers that are related to DT parts

Parts	Classification (the number of papers in this field)
Physical Parts	building (35) built environment(22) equipment (18) bridge(11) cultural heritage(9) structure(7) railway(6) disaster prevention and mitigation(5) construction site(5) indoor facility(5) tunnel(4) hydraulic engineering(3) metro(3) surveying and mapping(1) factory(1) municipal engineering(1) road(1) review(18)
Digitalization Methods for Virtual Parts	programming(44) Revit(43) platform(24) AutoCAD(15) smart phone application(10) Navisworks(8) Leica Cyclone REGISTER 360(6) Graphisoft ArchiCAD(6) Rhino(6) ArcGIS(5) Autodesk Recap(5) CloudCompare(5) finite element model(5) SketchUp(4) Unity3D(4) AR&VR(4) Bentley(3) Ecotect(3) EnergyPlus(3) RealWorkSurvey(3) xBIM(3) 3ds Max(2) Faro Scene(2) Solibri(2)
Connections	sensor(62) laser scanner/LiDAR(58) camera(43) cell phone/pad/mobile devices(22) Wlan/WiFi(20) actuator(17) GPS/GNSS/satellite(15) photogrammetry(13) thermal imaging(12) Bluetooth(9) RFID(8) survey(8) remote sensing(6) total station(6) PDA(5) robot(5) 3G/4G/GSM/UHF(4) QR code(3) radar(3) RTLS(3) ultrasonic(3) LAN(3) optical scanning(2)
Types of Data	point clouds(63) sensor data(61) images or videos(50) collected data(47) 2D drawings(29) thermal images(12) GPS or GNSS data(12) interview or questionnaire(8) RFID data(8) survey data(8) analysis data(7) remote sensing data(6) semantic information(5) map(4) geological survey data(3)
Services (Project stages)	design(5) construction(21) O&M(86) no clear stage(4) review(18)

Services (Functions)	management(47) DT creation and visualization (46) monitoring(43) detection(35) calculation and analysis(29) simulation(26) decision making(22) estimation(21) automatic control(17) optimization(13) diagnosis(12) retrofit(12) prognostics(9) navigation(4) clash detection(3) tracking(3) training(3)
Related Technologies	sensing(62) laser scanning(58) video/digital image processing(38) AI(17) semantic enrichment(17) photogrammetry(13) IoT(12) thermal imaging(12) GIS(11) GNSS/GPS(11) Bluetooth(9) UAV(9) RFID(8) web technology(8) LiDAR(7) remote sensing(6) robot(5) finite element(5) AR&VR(4) COBie(4) radar(3) RTLS(3) ultrasonic(3) optical scanning(2)

Based on the 134 papers' labels' co-occurrence analysis, DT research clusters can be divided into design, construction, operation and maintenance from the perspective of DT services. Besides, some papers only discuss DT creation approaches. Though most of them declared that they create DT for O&M, we establish a new research cluster for DT creation in addition to design, construction, operation and maintenance, as shown in Fig. 3. From the perspective of the physical part, DTs of related existing projects, environment, and surroundings which are called as-is physical parts, can be created during the project life cycle. However, at the design stage, target projects do not exist, which are called as-built physical parts. At the construction stage, the target projects are constructed and partially completed. Thus, DT can be created for partially as-built physical parts. At the O&M stage, the target projects are fully completed, and DT can be created for them.

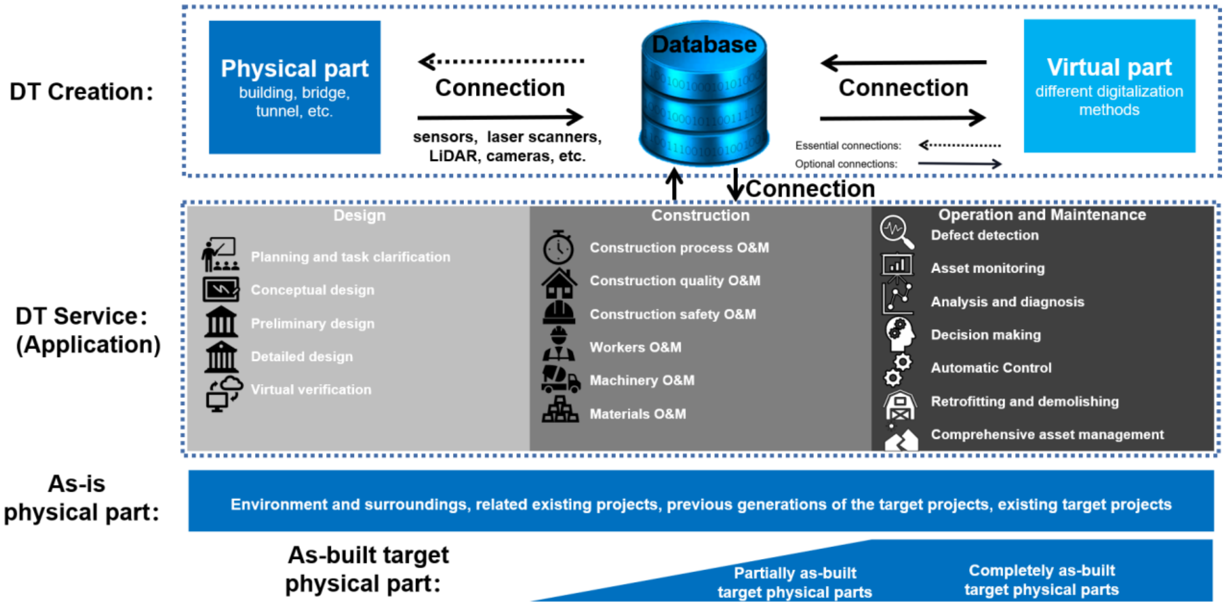


Fig. 3 Research clusters of DT applications in civil engineering

3.1 DT Creation

With the fast development of 3D surveying technology, generating a DT of existing facilities from spatial data becomes more feasible. Some studies only discuss how to build a digital twin for existing objects. Point clouds from laser scanners and LiDAR are the most common raw data for geometric information to create DT [102,132]. Images from cameras and data from sensors are also widely used to provide geometric information and non-geometric information for DT [10,28,35,72]. Various kinds of non-geometric information from sensors or other devices in the physical world can be added to the digital twin, such as type, colour, light, time, temperature, humidity, materials, weight, force, pressure, vibration frequency, flow rate, cost, energy consumption, gaseous emission (e.g. CO_2), manufacturer/vendor data, other semantic information, sustainability information, other environmental conditions, customer comments, etc.

[4,26,37,114,122,127]. They can enrich the information of DT and expand the functions of DT. DT creation is the cornerstone of DT applications. However, the main reasons that restrict DT's development are the efficiency and accuracy of DT creation [56,115,126]. Thus, new algorithms for DT creating are continuously proposed.

Heesom, et al. [51] developed a systematic collaborative heritage building information modelling (HBIM) to integrate tangible and intangible cultural heritage. Dore and Murphy [34] devised a new semi-automatic approach for generating accurate BIM facade models for as-is buildings from laser and image data based on two developments. O'Donnell, et al. [88] converted point clouds from a laser scanner into a building's exterior façade geometry as input data to establish Building Energy Performance Simulation (BEPS) models and carried on semantic enrichment manually. Laefer and Truong-Hong [62] proposed a method to automatically identify steel structure components from terrestrial laser scan point clouds to generate geometric shapes in a BIM compatible format. They employed kernel density estimation to determine the proper shapes and dimensions of the cross-section. An approach related to measured metrics was introduced, determining the best match of diverse cross-sections from a pre-filled library. Wei and Akinci [118] proposed a vision and learning-based framework using a shared convolutional neural network to perform localization and semantic segmentation simultaneously. Xiong, et al. [124] proposed an approach to generating 3D information models of structural components in an indoor environment using point cloud data collected by laser scanners. Lu, et al. [71] developed a semi-automatic framework to establish a systematic, precise and convenient digital twinning system based on images and CAD drawings. In the field of infrastructure, Lu and Brilakis [74] proposed a slicing-based object fitting method that can generate the geometric DT of an existing reinforced concrete bridge efficiently and accurately from four types of labelled point clusters. Ariyachandra and Brilakis [16] presented a method to detect railway masts using airborne LiDAR data by leveraging railways' highly regulated and standardized nature. The method's final deliverables include the mast positions' coordinates, detected point clusters, and 3D models of the IFC format masts. Cheng, et al. [30] proposed an approach to automatically identify types of components (rails, cross-sections, pipes, catenary equipment and refuges) and create parametric as-is BIMs for single-track railway tunnels using the Terrestrial Laser Scanning (TLS) data.

From these cases, most of the proposed DT creation approaches are effective for specific projects, and they are not universal for various kinds of projects. Due to the diverse characteristics and shapes, buildings, roads, bridges, railways, and other projects need to employ various appropriate DT creation methods. Besides, the identification and semantic enrichment of kinds of components determine whether the digital twin can be further used [1,20,45,92,121]. Besides, the algorithms for digital twin of outdoor structures need to consider the influence of the external environment. All in all, modelling approaches and applying new technology, including software and hardware, should be improved to realize accurate and efficient DT creation [32].

3.2 Design

At the design stage, target physical parts have not been built (target physical parts≠target projects. Some newly designed target projects have not been built, while some target projects have been built, such as retrofitting and reconstruction projects). A physical part is an essential element of a digital twin. However, DT can be made for the environment and surroundings, related existing projects, previous generations of the target projects, and existing target projects to assist in designing new projects or retrofit designing. Usually, DT should be estimated by design documents and other sources. Though there are not many cases related to DT applications for designing a new project in the civil engineering sector, DT for design has a clear workflow and great potential, as shown in 3 and Fig. 4.

3.2.1 Physical parts

From the perspective of physical parts, first of all, DT can be made for the environment, surroundings, and related existing projects according to point clouds, sensor data, design documents and other sources to assist in designing new projects. For example, Bansal [19] considered the spatial aspects of a project using 3D visualization, 4D modelling, virtual reality (VR), construction simulation and BIM. The impact of site topography and existing facilities in the surroundings on the site layout planning was considered using GIS, which can facilitate location-based analysis, modelling site constraints and spatial and non-spatial analysis on a single platform. Through integration and a high-fidelity model, DT can significantly improve the quality and accuracy of the design.

Second, DT can be established for the previous generations of the target project to study new projects and aid design. For example, in the manufacturing industry, a product and its DT can be made. Based on its DT and feedbacks on the product used in the physical world, the product can be upgraded, and the next generation of product can be produced [107]. Similarly, a DT can be made for a building or a bridge and their components. When engineers encounter a new building or bridge project with a similar type, the DT for the previous project can be used for research and simulation to design a new generation of the project [116]. Most DT applications in prefabricated structure design belong to this category.

Third, DT can assist in the design of retrofitting, reconstruction and expansion of the existing target projects. For example, Lydon, et al. [77] introduced a modelling method to develop a DT for a multifunctional building element to realize the thermal design of a heating and cooling system combined with a lightweight roof structure. They used high-resolution models to analyse and parametric geometry models to place hydronic pipework into a complex roof shape to obtain a lower-resolution building simulation model, which can help design the building system. Besides, road widening, reconstruction and expansion are typical projects that can employ DT. For example, in the highway widening project, the DT of the old existing road can be established using point clouds, sensor data, old design documents and other sources. Then, the design of the new lanes, shoulders, and side slopes along the old road can be conducted with the help of DT [103]. Retrofitting can be regarded as at the O&M phase of the old existing project which will be discussed in Section 3.4.6. However, sometimes, retrofitting can be regarded as a new project which includes design, construction and O&M. In this section, we just discuss the design phase of retrofitting.

3.2.1 Design stages

From the perspective of design stages, DT can assist in planning and task clarification, conceptual design, preliminary design, detailed design, and virtual verification [80].

First, at the planning and task clarification stage, DTs are established using data from multiple sources. Thus, designers can plan the potential project based on DT to make decisions, determine some constraints, and provide a project's overall framework and draft. Then designers can provide a clear task clarification which can assist in future design. Schrotter and Hürzeler [99] employed DT to assist in city planning and decision-making of the City of Zurich. 3D spatial data and their models transform themes of the city, such as buildings, bridges, vegetation, etc., to the digital world, are being updated when required, and create advantages in digital space.

Second, DT can integrate a variety of data from related existing projects, environment, surroundings, design documents and other sources to assist in conceptual design, preliminary design, and detailed design [19,77]. The same set of DT models can be transferred to all design stages, which can facilitate designers to efficiently design, iterate schemes and collaborate. In this process, DT needs to be continuously evaluated and upgraded by the design documents and obtained data in the physical world.

Third, by leveraging data from multiple sources, DT itself can be estimated, and the design can be evaluated using DT to reduce design defects and inconsistencies between the actual and expected design using simulation and analysis in the virtual part instead of the physical world. Thus design can be effectively revised, improved, updated and verified without too much time, money and labour consumption. For example, Oti, et al. [90] proposed a framework for utilizing feedback loops from building energy consumption to inform and improve design and facility management in a DT environment using laser scanners and cameras, which can bridge existing gaps between phases of a building's life cycle. Eguaras-Martínez, et al. [38] conducted building simulations to evaluate building energy performance considering individuals' real behaviours in a real pilot site to reduce energy and money consumption to assist designers and engineers. They found differences of up to 30% (approximately) by merely including individuals' real behaviours in building simulations. However, these cases cannot prove that the design using DT is more efficient than traditional methods. Advanced algorithms and tools are essential to improve the efficiency of design in the future.

Table 3 Research clusters of DT at the design stage

Categories	Research clusters	Illustrations
Physical parts	Environment and surroundings	See ① in Fig. 4
	Related existing projects	See ② in Fig. 4
	Previous generations of the target project	See ③ in Fig. 4
	Retrofitting and reconstruction of the target project	See ④ in Fig. 4
Design Stages	Planning and task clarification	Make decisions, determine constraints, provide a project's overall framework and draft, clarify tasks
	Conceptual design	Provide ideas of the design and consider their advantages and disadvantages
	Preliminary design	Before submitting a fixed bid quotation, control project quantities, costs and plan the project thoroughly
	Detailed design	Describe each aspect of the project in detail completely and systematically through modelling, drawings, and specifications
	Virtual verification	Conduct simulation and analysis in the virtual world, revise, improve, update and verify design

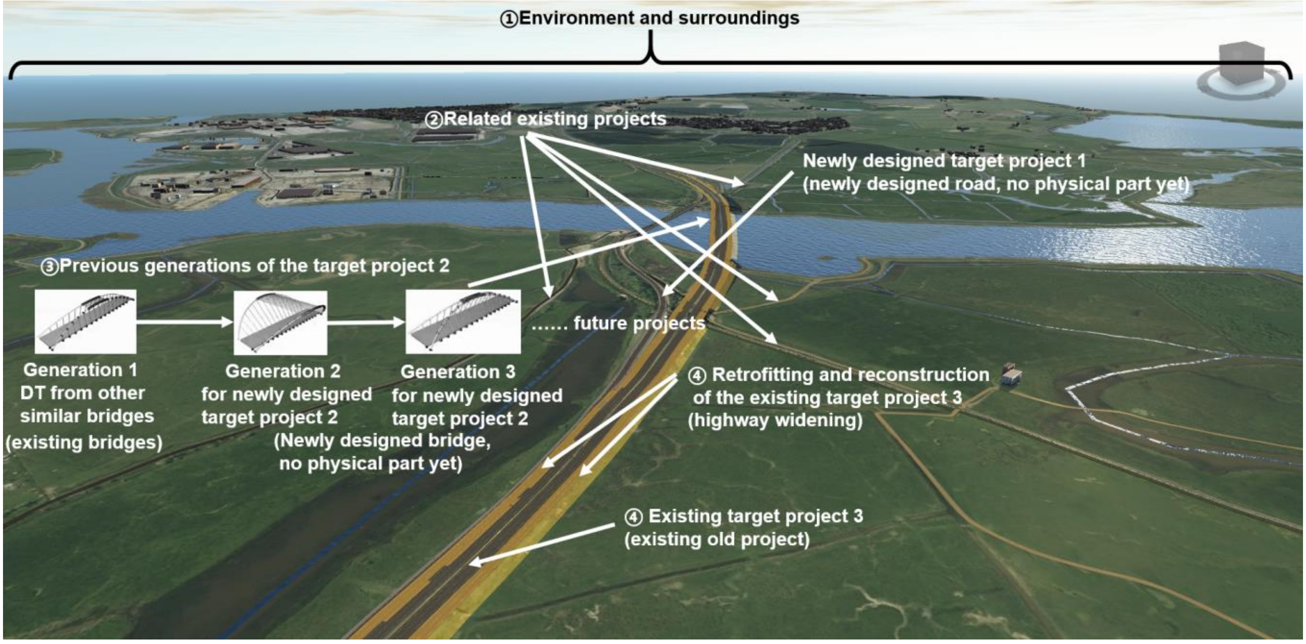


Fig. 4 DT at the design stage

3.3 *Construction*

In the era of digitalization, the smart construction site is developing very fast in that many digital means have been implemented, such as CPS, BIM, laser scanning, sensing, RFID, web technology, and more. Sometimes, BIM can be employed in construction and sensors and other connections between the physical and the real world. Sometimes, BIM and CPS can be used in construction together in such a way that they usually possess the essential elements of a DT (BIM+CPS $\neq$DT, sometimes BIM+CPS can be DT). On the one hand, the methods of digital twinning for the existing environment and entities on-site should be developed to realize timely, efficient, accurate model reconstruction. Generally, laser scanners, LiDAR are employed to obtain point clouds on-site for modelling [112]. On the other hand, the connections and real-time communication between physical parts on-site, virtual parts, and the central database is essential to facilitate real-time monitoring and management. For example, DT can help develop the system architecture of BIM and prefabrication housing production (PHP) via communication and interaction with the central database and can be implemented to benefit various stakeholders to facilitate the integration [68]. At the construction stage, the physical parts of the target project have not been completed. Thus, DT can be made for other related existing projects, related environment, related surroundings, partially as-build target projects to facilitate construction monitoring and management, including construction progress, quality, safety, workers, machinery, materials monitoring and management, as shown in Table 4.

Table 4 Research clusters of DT at the construction stage

Categories	Research clusters	Articles
Functions	Construction Progress Monitoring and Management	[5] [27] [68] [76] [82] [94] [112]
	Construction Quality Monitoring and Management	[6] [25] [49] [57] [86]
	Construction Safety Monitoring and Management	[8] [44] [55]
Targets	Workers Monitoring and Management	[7] [17]
	Machinery Monitoring and Management	[69] [131] [133]
	Materials Monitoring and Management	[29]

3.3.1 Construction Progress Monitoring and Management

For construction progress, visualization and computer vision techniques can be employed to monitor detailed interior construction progress using an object-based approach. As-planned 3D models from BIM and as-built photographs are visualized and compared, and the as-built interior construction objects can be decomposed to generate the status of construction progress automatically [94]. A CPS approach can also be employed to enhance bi-directional coordination between virtual models. A physical construction and prototype system can be established to improve real-time monitoring and control of the construction facilities, track changes and model updates, information exchange between the design office and the construction site, and real-time documentation of the as-built status of high-value components [5]. For example, Matthews, et al. [82] studied the effectiveness of cloud-based BIM in real-time information delivery to support construction progress monitoring and management of reinforced concrete structure construction based on action-based research. Bueno, et al. [27] proposed a novel automatic coarse registration methodology between BIM models and as-built scanned data called the '4-Plane Congruent Set' (4-PlCS) algorithm to realize construction quality and progress control. Lundeen, et al. [76] realized autonomous sensing and modelling of construction objects for construction robots to adapt to unexpected situations and to perform quality work using two model fitting techniques of construction components, called clustering and iterative closest point (CICP) and generalized resolution correlative scan matching (GRCSM). In construction progress monitoring and management, the timeliness of DT is crucial.

3.3.2 Construction Quality Monitoring and Management

For construction quality monitoring and management, a Scan-vs-BIM processing system can be employed to track built status and assist in automated and robust quality control, including estimating the emerging performance metric per cent built as designed [25]. Spatial change detection can be realized by comparing the 3D as-built models derived from laser scanning data with the as-designed BIM models to achieve computationally efficient detection and management [57]. Besides, based on IFC schema, as-designed BIM-based on-site observations can be for inspected building elements automatically by receiving inspected object's actual types and inspection details, including the detected defects/changes, responsible actors, as-built/as-is types, captured images, and the time and the date of the inspection to retrieve the element's semantics and identify the discrepancies between the as-built/as-is and as-designed object status. Inspection details and user entries are automatically recorded in the BIM and assigned to objects to enable potential diagnostics and tractability [49]. A framework was proposed by Nahangi, et al. [86] for the automatic and systematic development of realignment actions required to achieve an ideal status to modify defective construction assemblies through 3D imaging and an inverse kinematics analogy. Akanmu and Okoukoni [6] tracked building components installation automatically using proximity data from swarm nodes. During the installation process, proximity data are obtained from tagged steel components compared with the design models' data. In this field, DT's accuracy plays an important role in comparing the actual quality with target quality.

3.3.3 Construction Safety Monitoring and Management

Based on a CPS and DT concept, a smart construction site framework can be established for safety management, enabling personnel, mechanical and other risks on-site to originate warnings and be controlled [55]. Golovina, et al. [44] approached the bottom of Heinrich's safety pyramid by providing an in-depth quantitative analysis of close calls to address fatal construction workplace accidents related to the too-close proximity of pedestrian workers to construction equipment or hazardous materials. The obtained information was embedded in simplified geometric information models that users on a construction site can retrieve, easily understand, and adapt to existing preventative hazard recognition and control processes. Akula, et al. [8] realized real-time monitoring for drilling process hazards by processing and incorporating point clouds from 3D imaging technologies into the drilling process. However, these proposed methods have not been proved in more complex conditions. The DT's development in this field is in its infancy.

3.3.4 Workers Monitoring and Management

For worker management on site, a system called the worker trajectory analysis system was developed by Arslan, et al. [17], which is based on a real-time Bluetooth low-energy (BLE) beacons-based data collection and pre-processing trajectory subsystem, ontology-based semantic trajectories for dynamic environments model, hidden Markov model and Viterbi algorithm using a BIM model, to understand worker movements in dynamic construction environments, including moving and changing objects. A CPS based postural training environment was developed by Akanmu, et al. [7] where workers can practice performing work with reduced ergonomic risks using wearable sensors, Vive trackers, machine learning and virtual reality to track body kinematics and engagement with physical construction resources. It can provide feedback via an interactive user interface.

3.3.5 Machinery Monitoring and Management

DT can monitor, manage and control the machines to realize an efficient, accurate and safe construction. Yuan, et al. [131] established a temporary structure monitoring system based on CPS that integrates the virtual model of a temporary structure and the physical structure on the construction site according to end-user requirements and system requirements. Liu, et al. [69] developed a framework for efficient roller compaction monitoring and controlling in asphalt pavement construction based on CPS, which includes five modules: the data acquisition module and data transmission module remote servers, in situ control module, and monitoring terminal. Zhou, et al. [133] developed a cyber-physical-system-based safety monitoring system for blind hoisting in metro and underground constructions. They applied it to Wuhan Metro's Sanyang road tunnel successfully to simulate and monitor the hoisting process to avoid the unsafe state of cranes and the hoisted cutter wheel using IoT technologies. At this stage, the compatibility of sensors and machinery and the timely transmission of data are important. Also, the sensors used for monitoring must not affect the regular operation of the machine.

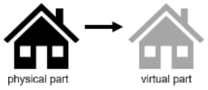
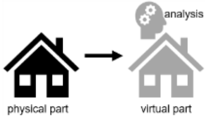
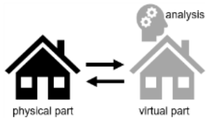
3.3.6 Materials Monitoring and Management

For construction materials management, a new workflow was designed successfully by Chen, et al. [29] to include the use of detailed look-ahead plans when using BIM and RFID technologies according to lean theory. It is modelled using business process modelling notation, which can accurately track and match both the dynamic site needs and supply status of materials. The new workflow helps contractors better monitor on-site situations and differences between the actual and planned material requirements and alert suppliers if it is necessary. However, the realization of these functions is under a set ideal and simple situation, and whether the technology can be applied to the complex supply chain on-site needs to be further proved.

3.4 Operation and Maintenance

At the O&M stage, DT can contribute substantially to asset management in the O&M phase, and there are many successful cases [70]. They can be divided into three categories, as shown in Table 5. The first one is "monitoring", which focuses on obtaining data to update the virtual parts from the physical parts, including defect detection and asset monitoring. The second one is "analysis", which focuses on analysis using virtual parts after collecting data, including analysis and diagnosis and decision making. The third one is "action", which not only focuses on collecting data from the physical parts to the virtual parts, but also focuses on doing something with the physical parts using virtual parts, including automatic control and retrofitting and demolishing. By obtaining geometric information, DT can be employed to detect defects. By leveraging sensors, DT can be employed to monitor existing projects. Based on obtained data by physical-virtual connections, the physical parts' status, diagnose problems and make decisions can be analysed. In addition to data transmission from physical parts to virtual parts, virtual parts also can convey data to and control physical parts. Besides, the DT can provide a digital replica for the existing project to assist in retrofitting and demolishing. Finally, by leveraging various new technologies simultaneously, DT can realize comprehensive asset management such as disaster prevention and mitigation.

Table 5 Research clusters of DT at the O&M stage

Categories	Research clusters	Number of articles
Monitoring 	Defect Detection	[13] [14] [15] [41] [53] [60] [63] [83] [84] [85] [89] [91] [96] [105] [125]
	Asset Monitoring	[11] [18] [21] [24] [36] [39] [40] [47] [48] [52] [58] [73] [75] [97] [100] [101] [104] [130] [134]
Analysis 	Analysis and Diagnosis	[12] [21] [33] [81] [87] [106] [123] [128] [129]
	Decision Making	[31] [67] [79] [109] [110]
Action 	Automatic Control	[2] [23] [98] [117]
	Retrofitting and Demolishing	[9] [43] [50] [59] [64] [93] [113] [119]

Comprehensive Asset Management	[78] [120]

3.4.1 Defect Detection

Focusing on geometric information, the DT provides a visual and efficient way for inspection and defect detection by processing forms of data, such as point clouds, digital images, thermal images and sensor data from laser scanners, cameras, thermal imaging devices, sensors and other devices. Some of them are similar to Scan-to-BIM and Scan-vs-BIM. Some are similar to traditional health monitoring using sensors. Cultural heritage, buildings, bridges, roads, and railways can employ DTs to inspect projects and detect defects. A DT can also detect as-built defects and deviations from the original design using point clouds [14] and images [60]. However, the lack of digital twinning's efficiency hinders its development. A workflow was proposed by Lagüela, et al. for the automatic generation of textured as-built models, beginning with data acquisition and continuing with geometric and thermographic data processing using laser scanning, infrared thermography and photography. Their methodology can be applied to defect detection, retrofit decision making and retrofit work efficiently [63]. Mill, et al. [84] proposed a systematic method for collecting accurate survey data using a terrestrial laser scanner combined with a total station and establishing a BIM model as the basis of a digital management model. It can detect and define facade damage, find the as-built deviations from the design and realize clash detection between structures. Gao, et al. [41] introduced six feature-based matching methods that can match segments of point clouds from laser scanners with components modelled in BIM to match the mechanical equipment and piping system captured by point clouds to the corresponding objects modelled by the designed BIM models. All in all, these advanced point clouds and image processing methods are the cornerstones for defects detections.

Additionally, other visualization approaches such as VR and game engines and data storage and transmission methods are implemented in bridge defect detection workflow. A next-generation integrated bridge inspection system called SeeBridge was introduced. The "Information Delivery Manual" (IDM) is compiled to specify the technical components, activities and information exchange in the SeeBridge process, and a model view definition (MVD) bound to the IFC4 ADD2 data schema standard is prepared to specify the data exchange schema to service the IDM. The IDM and MVD support the research and development of the system by strictly defining the information and data that constituted the bridge engineers' knowledge[96]. The bridge information modelling (BrIM) concept was introduced, and a DT model can be created using laser scanners and cameras for heritage railway bridges with few as-built records to inform the initial feasibility condition assessment and subsequent design, construction and operations [83]. Omer, et al. [89] proposed a novel approach for bridge inspection that can make DTs for bridges using LiDAR, and the DTs can be inspected in a VR environment using the developed VR app based on a game engine called Unity 3D. However, they focused on visualization much more than defect detection. An effective workflow for defect detection is essential. Shim, et al. [105] developed a bridge maintenance systems to achieve a more reliable decision-making workflow. In their work, a detailed solution was proposed to enhance the bridge maintenance process using two parallel solutions: a maintenance information management system based on a DT and a digital inspection system using lasers, sensors and image processing. Xu and Turkan [125] developed a novel, systematic bridge inspection and management framework to improve the current efficiency of projects using camera-based unmanned aerial systems with computer vision algorithms to collect and process inspection data and using bridge information models (BrIM) to store and manage all related bridge inspection information. Isailović, et al. [53] proposed a point cloud-based spalling damage detection method for bridges using laser scanned data and images and an approach to integrating the damaged components into BIM through semantic enrichment as-built IFC model.

DT also can assist in historical building defect detection and protection. Antón, et al. [15] analysed the 3D modelling accuracy for creating historical building information models (HBIM) using point clouds, images and BIM software called Rhino. The modelling process analysis is based on a three-stage semi-automatic method, including (a) optical and terrestrial laser scanning, (b) meshing process, and (c) assembling the 3D solid model into the HBIM. Angjeliu, et al. [13] studied historic masonry buildings' structural system integrity by developing DTs' concept and implemented it in the Milan Cathedral. They created a precious digital model that integrated practical physical reality and applied it to study the system's structural response, its preventive maintenance and enhanced operations. Piaia, et al. [91] introduced an asset management tool for historic buildings, a software solution used for condition assessment on-site and management of assets with embedded BIM software. DT can provide a digital replica for existing historical buildings; thus, the buildings can be protected in time to avoid damages. Mol, et al. [85] presented the application of a methodology that used common HBIM (Historic Building Information Modeling) software in combination with results obtained from non-destructive testing and geometric surveying, allowing it to perform modeling, analysis and storage of geometric data, levels of decay and lack of material of timber structures within a tridimensional space. However, generally, historical buildings do not have standard components as modern buildings according to design standards. Thus, their digital twinning methods are not necessarily universal to other kinds of historical buildings, but the proposed workflows are very valuable.

3.4.2 Asset Monitoring

Focusing on geometric and non-geometric information, the DT employs sensors to upgrade the data in time for the accounting of virtual parts from physical parts to realize asset management. In the field of buildings, Kang, et al. [58] established a new monitoring framework based on BIM and IoT; it has a comprehensive view of the buildings' state and improved information utilisation efficiency. Fargnoli, et al. [40] integrated BIM-based approaches in a Product-Service Systemcontext to improve the management of building equipment O&M, and they implemented the framework for elevators of an existing building. Lucas, et al. [75] proposed an object-oriented product model in the context of developing an information management framework for healthcare facility based on Unified Modelling Language cases to check the information requirements of existing healthcare facility maintenance operations. Arslan, et al. [18] designed a framework called "occupant behaviour in dynamic environments" (OBiDE), which provides a "blueprint" to integrate existing DNAS (drivers, needs, systems, actions) ontologies with their semantic trajectory enrichment model to better understand the behaviour of occupants in facility management applications by tracking the dynamicity of the building locations. Bonci, et al. [24] developed a BIM-based cyber-physical system for the real-time automated monitoring of buildings during their regular operations, which is assessed through a customized simulator. The DT model can mirror the physical system and store the actual status recorded by the building to assist facility managers in making decisions.

In the field of civil infrastructure, the infrastructure Smart Service System (iS3) concept was proposed based on digitalization techniques and integrated construction and maintenance of infrastructure, which included five levels: foundation layer, data layer, service layer, application layer and user layer, based on BIM, GIS, IoT, and web technology [134]. Boddupalli, et al. [21] employed a BIM and an integrated digital representation platform of structural health monitoring (SHM) for bridges, organizing and visualizing large amounts of sensor data and subsequent structural health information for a long time. It facilitates periodic maintenance and risk management and condition assessment and disaster mitigation of structures from long-term monitoring data. Based on a DT, sensing and video monitoring, Yin, et al. [130] proposed a novel framework to improve the sustainable O&M of utility tunnels, which mainly included three modules: BIM model, O&M database, and monitoring system, which can facilitate the information integration and communication of utility tunnels. Shafiee, et al. [100] created a dynamic demand assignment hydraulic DT model in which consumption data were allocated to nodes to update the water network model with streaming data from the data centre without interrupting the running of a hydraulic simulation. Similarly, a semantic knowledge management service and domain ontology was proposed by Howell, et al. based on web technology, IoT and sensing that combines the household social-technical water system with the clean waste network at an urban scale to provide support for new cloud edge solutions, thereby providing value-added services for consumers and network operators [52]. From these cases, it can be concluded that DT can reflect the real-time status of infrastructure in the physical world by data conveying using sensors. In a large-scale infrastructure project, where sensors should be set that can effectively monitor the project is very important.

For structure monitoring, Saltari, et al. [97] reconstructed the displacement field throughout the structure from pointwise measurements under noise sources. The developed estimator employs a Proportional Observer (PO) or a Multi-Resolution Proportional Observer (MR-PO) to improve its accuracy. The considered numerical test case is based on a straight, uniform beam with an unmodeled stiffness reduction provided by a notch. The obtained results evaluate the effectiveness of the combination between the PO concept and wavelet multi-resolution analysis as a tool for developing DT models based on experimental data.

For asset management and monitoring, data storage should also be focused on. Halmetoja [47] proposed a new concept called the conditions data model (CDM), which describes how BIM and big data can be combined in the same interface to provide new value to stakeholders. A system with a new method for automatically correlating and updating actual thermal property measurements using BIM elements in the gbXML schema was developed by Ham and Golparvar-Fard. [48]. Shalabi and Turkan [101] employed IFC models to link and present alarms reported by facility management systems, such as building energy management systems (BEMS) and building automation systems (BAS), with related data from computerized maintenance management systems (CMMS). Edmondson, et al. [36] introduced a smart sewage asset information model (SSAIM) prototype for the existing sewage network. The SSAIM is developed using IFC4 incorporated distributed smart sensors to realize real-time monitoring and reporting on sewer assets' performance to facilitate real-time flood prediction. Andriamamonjy, et al. [11] created several Modelica-based grey box models according to existing rule-based IFC to Modelica interfaces, which consider the building's specific information and characteristics to realize automatic connections between the models and the building monitoring system to produce high precision models that are valid for all seasons. Lu, et al. [73] introduced an anomaly detection system based on a DT for asset monitoring using an HVAC system, and its data integration method was based on IFC in daily O&M management. In the field of asset monitoring, an appropriate design of the database's structure and the selection of the data format are complicated issues that need to be paid attention to. Though IFC, XML formats have not been perfectly developed and have some weaknesses, they can be widely used for asset monitoring and management. For example, the IFC format has not well designed for roads.

Additionally, DT can provide a visual environment for asset monitoring and management. El Ammari and Hammad [39] developed a BIM-based MR framework to support facility site tasks, integrating multi-source facility information, BIM models, and feature-based tracking in an MR-based setting to retrieve information based on time. It also supports the field workers' locations, visual inspection and O&M, and remote collaboration and visual communication between field workers and office managers. Shelden [104] proposed a network of instrumented spaces based on the Georgia Institute of Technology campus, addressing aspects of campus life that connect their digital infrastructure using CPS. Their building energy system allows several zones within a larger space to be independently measured and controlled. BIM models, energy zone information, building controls data streams, occupancy and environmental sensors, and energy simulations can be displayed in a diverse set of visualization technologies. However, these examples are usually only visualized using VR, AR and MR for visualization itself rather than the practicality. Whether it can effectively replace traditional monitoring work still needs to be tested in practice. In addition, more workers who can work with visualization tools for asset monitoring need to be trained.

3.4.3 Analysis and Diagnosis

Focusing on geometric information, a DT can produce high-fidelity 3D models for simulation and mechanical calculation. To an extent, we can regard some finite element models for existing structures as DTs. For example, Matsubara, et al. [81] developed an aseismic renewal method for the plaster finished ceiling in a historic building, including earthquake resistance by fixating the ceiling base and dropping prevention using mesh sheet steel wire. It was verified that the developed aseismic reinforcement method had acquired earthquake resistance performance through experiments and numerical analysis. Boddupalli, et al. [21] employed BIM and an integrated digital representation platform of structural health monitoring (SHM) for bridges, organizing and visualizing large amounts of sensor data and subsequent structural health information for a long time. By comparing the current SHM data with the Finite Element model's predicted response, the proposed visualization tool will expand the decision-making capabilities of SHM within the BIM to identify the structural performance under various weather and operational conditions. Ye, et al. [129] conducted a visual inspection, operational monitoring, forced excitation testing, controlled load testing, non-destructive probes, long-term monitoring, finite element modelling, parameter identification and 3D DT development for a 30-year-old expressway bridge in New Jersey, which enabled them to determine the root causes of multiple complex performance defects systematically. In addition to analysing the current status of structures, DT also can be employed to predict the status in the future. Tahmasebinia, et al. [106] presented a preliminary finite element model to analyse creep and shrinkage effects on the prestressed concrete ribs of the Sydney Opera House. A linear static analysis was performed to investigate the instantaneous impacts of dead and wind loads on the complex concrete structure. In addition, a quasistatic analysis was performed to predict the effects of creep and shrinkage due to dead load on the structure in 2050 to discern its longevity. In these cases, the combination of DT and finite element has not been fully explored. In the civil engineering sector, the finite element is widely used. However, the related research and application of DT have just started. The combination of DT and finite element has great potential.

Additionally, based on DT models and collected data, calculations and analysis can be performed to assess and diagnose the physical part when determining specific problems. To make so, Dong, et al. [33] developed information infrastructure for energy fault detection and diagnostics based on BIM, which streamlined the information exchange process and was implemented in a building. Yang and Ergan [128] proposed a user-centred and iterative workflow to design and implement a visualization platform to support troubleshooting of HVAC-related problems. Natephra, et al. [87] developed a system of integrating time-stamped 3D thermal data in the BIM with spatiotemporal thermal and air temperature data using sensors and thermal imaging; this system could analyse thermal performance and assess the thermal comfort level. Andriamamonjy, et al. [12] developed an automated toolchain that combines a BIM-to-BEPS (building energy performance simulation) tool with a model-based FDD (fault detection and diagnosis) approach to realize an automated calibration and a novel model-based FDD with fewer experts involved, which was applied to an actual AHU. Xie, et al. [123] established an AR-based automated environmental anomaly detection and fault isolation method to help facility managers detect anomalous temperatures and solve problems that affect the building occupants' thermal comfort using a developed decision-making tree based on fault tree analysis (FTA). In these cases, physical-virtual connections can obtain data from physical parts, and DT can provide virtual entities and environment to be analysed and assessed representing the physical parts. However, most of them conducted the analysis and diagnosis only based on limited kinds of obtained data and limited kinds of indicators. Thus, the analysis is not very comprehensive and objective. For further research, the analysis and diagnosis process using DT should be better based on comprehensive data and indicators.

3.4.4 Decision Making

DT can represent physical parts in the virtual world; thus, based on DT, some decisions can be made. Li, et al. [67] introduced an iterative maximum likelihood estimation indoor positioning algorithm to support building emergency response operations using radio frequency signal data, collected by existing sensing infrastructure in a building and incorporating building geometric information available in BIM. Ma, et al. [79] proposed a data-driven approach for decision-making on equipment maintenance by integrating three technologies: reliability-centred maintenance (RCM), BIM and GIS. BIM and GIS were integrated to support the acquisition and update of data required for the RCM process. Besides, DT can provide a virtual environment for path planning. Tashakkori, et al. [109] proposed a novel indoor emergency space model based on IFC, which integrates 3D indoor architectural and semantic information needed by first responders during indoor disasters with outdoor geographic information to improve situational awareness about both the interiors of buildings and their interactions with outdoor components. It can realize both decision-making and navigation by indoor spatial analysis and shorten travel time. Chou, et al. [31] developed a dynamic rescue/evacuation procedure for fire departments using existing firefighting equipment, Bluetooth sensors, global positioning information, an optimal fire rescue path-planning algorithm, and visual technology. By providing firefighters and trapped occupants, real-time updates for optimal path planning in a dynamic environment can provide fire departments with accurate and useful information about the fire site in real-time. Tran, et al. [110] proposed a novel shape grammar approach for efficient generation of 3D parametric models of complex indoor environments from point clouds efficiently and accurately by using a simple primitive and iterative application of grammar rules governed by a production procedure, which can reconstruct both building elements and navigable spaces along with their topological relations. The output models can realize indoor path planning at varying granularities. These decision-making cases are hard to be conducted in the physical world without DT. Similar to Section 3.4.3, the reasonable decision-making process using DT should be based on comprehensive data and indicators.

3.4.5 Automatic Control

In addition to monitoring, DT can also convey data from virtual parts to control the physical parts using actuators. Akanmu, et al. [2] proposed an approach to monitor and control light fixtures using cyber-physical systems integration between virtual models, physical light fixtures and their bidirectional coordination. Schmidt, et al. [98] proposed a framework to enhance old and modern buildings' energy efficiency by integrating available instruments into data-driven predictive cyber-physical systems. Wang, et al. [117] proposed an occupancy-linked energy-cyber-physical system to extract three forms of occupancy information, which can link energy management systems and CPS. Their method can address the excessive energy consumption caused by overheating and overcooling and discomfort due to poor thermal and ventilation management. Böke, et al. [23] developed a CPS and DT for a building facade to realize automated adaptive functions, considering sun protection, ventilation and heating and cooling functions using a prototype for automated adaptive façade, sensors, microcontrollers, WiFi and brokers, and actuators. Sometimes, when referring to this type of applications, a cyber-physical system is completed, or we can regard it as a cyber-physical system with corresponding twinning 3D models.

3.4.6 Retrofitting and Demolishing

When we want to accomplish a goal for existing projects, a DT can establish a virtual version of entities and environments in the real world, including geometric and non-geometric information, paving the way for work related to old existing projects, such as reconstruction, retrofit and demolishing. DT can provide a pre-retrofit model that can efficiently acquire and integrate various building data forms to gain a comprehensive understanding of the building to be renovated [43]. DT can employ 3D laser building scanning and the BIM2BEM to increase productivity over the time-consuming and labour-intensive conventional energy optimization processes and analysis-driven retrofit decision making for existing buildings [59]. By surveying and documentation of a building's existing status and meeting the requirements to build a continuous digital chain DT can encompass the various project stages from the survey to the site assembly of the elements using technologies such as 3D laser scanning and BIM to improve the energy efficiency of existing buildings and assist in retrofitting [64].

For example, Rocha, et al. [93] employed BIM2BEM to simulate retrofitting schemes by the comprehensive application of BIM and building energy modelling to make retrofitting decisions based on an economic analysis indicator called savings-to-investment ratio (SIR). The analysis results proposed creating an enclosed heated waiting area to improve the passengers' thermal comfort. Harmathy, et al. [50] proposed an integral methodology for overall energy performance improvement of office buildings based on a multi-criterion optimization method, high-precision BIM programs and dynamic energy simulation engines, which can be applied widely to energy performance refurbishment of as-is office buildings. Alhaidary, et al. [9] established a 3D energy model for a modern office building using BIM, infra-red thermography, and heat flux sensors, simulating real-life lack-of-information scenarios with little input from the HVAC system. Based on the DT model, some passive heat-gain reduction measures through the building envelope were analysed and compared with each other, such as the building's orientation, shading, insulation levels, and window performances. In the field of infrastructure, starting with geological field mapping in tunnels, Weichenberger, et al. [119] proposed a process for transforming all geological survey data into data structures in BIM systems for later use. The process can provide a 3D information ground model, which can be maintained as part of the structure's DT through the life cycle, to assist the operations, maintenance, enlargement and renaturation. Most of the cases are related to buildings' environment. DT can bring existing buildings and infrastructure to the virtual environment where complex simulation and integrated analysis can be conducted instead of the physical world to provide an appropriate scheme for retrofitting. It can reduce time, labour and money consuming. The accuracy of DT creation, appropriateness of the simulation and the exactness of the analysis are important. For infrastructure, some reconstruction and expansion projects can be conducted based on the DT of the existing project, such as highway reconstruction and expansion.

DT also has a broad prospect to make the DT model for old as-is projects to manage demolishment. For example, Volk, et al. [113] developed a united system with hardware sensors. The system has software modules for building information acquisition, 3D reconstruction, object detection, building inventory generation, and project plans optimization. In such a way, planners, experts, or decision-makers can inspect a building and record, analyse, reconstruct, and store the building by digital means simultaneously. Based on the building's condition as automatically captured and processed by the sensors, the system uses the available resources and the required decontamination and deconstruction activities to execute the building deconstruction's comprehensive project planning. Also, it considers the recovery of secondary raw materials, the use of renewable resources, employee qualifications, on-site logistics, material storage and recycling options to optimize the time and cost.

3.4.7 Comprehensive Asset Management

DT can leverage technologies, such as IoT, sensing, GIS, laser scanning, and photogrammetry, to monitor geometric and non-geometric information and control the physical parts of the existing projects to realize comprehensive asset management, such as disaster prevention and mitigation. Welch, et al. [120] introduced three ways that DT can assist in assessing and mitigating seismic risks: (1) BIM can provide valuable data on the characteristics of structural and non-structural elements in buildings to achieve a reliable overall seismic risk assessment; (2) the damage information obtained from the structural health monitoring technology before and after an earthquake can be used for self-diagnosis; and (3) in building management, an emergency management hub is established to implement control procedures to monitor and ultimately shut down damaged mechanical services after an earthquake. Lyu, et al. [78] developed a novel system for flood risk evaluation of a metro system based on GIS, GPS, BIM and remote sensing, which can realize early warning and inundation risk management of metro systems. However, due to the low frequency of the disasters' occurrence, the reliability of the disaster prevention and mitigation using DT is hard to be proved in practice.

4 Discussion

Based on the review and analysis in Section 3, this section discusses the existing challenges and DTs' future development in the civil engineering sector.

4.1 DT Creation is the Foundation and the Difficulty of DT Development

Most of the 134 papers are about generating virtual parts of their physical counterparts. The virtual part is the core and foundation of a DT, based on which diverse applications can be realized. The limitations of making virtual parts' efficiency and accuracy are mainly due to data acquisition, data processing, modelling methods, and modelling tools. Usually, some devices are employed to obtain data, such as sensors, laser scanners, LiDAR, cameras, RFID devices, mobile phones, tablet computers, or other mobile devices. Then, they develop several data processing methods and algorithms and employ many kinds of software to process raw data such as sensor data, point clouds, images, and other format data. The quality of the raw data and processed data, and the efficiency of the data acquisition and processing can influence the modelling process to a large extent. Based on the processed data, scholars propose various algorithms and use many kinds of software to make DTs for target entities or environments in the real world. Completing a DT model is not the terminal point, because, after that, whether the DTs can be employed in target services should be verified. Otherwise, the DT fails. There is no doubt that digital twinning or making virtual parts is a challenging problem. Furthermore, in civil engineering, projects, such as buildings, bridges, roads, tunnels, railways, metros, and equipment, have diverse shapes and components that require various modelling methodologies, algorithms and software.

Making virtual parts has become one of the most important research trends in the DT domain. Scholars and engineers should continue researching modelling approaches for all kinds of projects and keep pace with new technologies. Simultaneously, advanced algorithms, software and hardware should be developed as feasible tools for modelling. Finally, the DT models can be employed to realize the target services and applications. Otherwise, the DT approach would be meaningless.

4.2 DT Provides Basic and Advanced Data for Design

A physical part is an essential element of a digital twin. However, at the plan and design stage, physical parts of the target project have not been built. Generally, DT applications at the plan and design stage refer to DT for the other related existing projects, related environment and related surroundings. First of all, since DT can provide a digital replica for the physical part, DT can collect, compile and store data from the physical world, which can provide various forms of data for design. Second, compared to traditional methods, sometimes DT can provide advanced data such as high-fidelity 3D models, environment and even 3D information models to assist in design. Third, DT can provide an integrated virtual environment and integrated data. Thus, the design can consider many factors and can be more reasonable using DT. Forth, based on DT, some simulation and analysis can be carried out to provide more advanced data for design. In addition, with the help of AI, DT can provide more intelligent and complex design. Generally speaking, DT can promote high-precision, high-quality, deeper, and more integrated design. However, since the development of DT in civil engineering is in its infancy and limited by current technology and tools, a design using cannot be proved to be more efficient than traditional methods.

4.3 DT Promotes Smart Construction

At the construction stage, BIM and CPS are widely applied to projects. When virtual models are connectted with target physical parts in BIM applications or in CPS applications, when making corresponding 3D models for target physical parts, DTs usually emerge. In addition to the modelling methods mentioned in Section 4.1, attention is being paid to developing new technologies for connections, such as laser scanners, cameras, total stations and other devices for updating geometric information in time, and sensors, RFID, mobile devices (Pads, mobile phones), etc. for updating non-geometric information in time. At the project construction stage, the DT is employed to monitor construction sites and equipment and to realize construction with timely and integrated management, including process, quality, safety, workers, machinery and materials monitoring and management. With the development of DTs together with these methods, construction can be brought into the virtual world, in such a way that some simulation, calculation, analysis, optimization, and management can be conducted virtually at a low cost. The DT approach can promote the development of smart construction.

4.4 DT Plays an Important Role in O&M

O&M stage has the most DT application cases. DTs are made for as-is projects or equipment and establish connections between the physical parts and the virtual parts to update the real-time conditions using the advanced technologies mentioned above to realize operations and maintenance.

The first category of the research clusters is "monitoring", which focuses on obtaining data to update the virtual parts from the physical parts, including defect detection and asset monitoring. When focusing on geometric information, the basic level of O&M DT applications is detecting defects and assessing the status of infrastructure, buildings, cultural heritage, equipment and inner structures using laser scanners and cameras. When focusing on non-geometric information, the basic level of O&M DT applications is monitoring using sensors. DTs are employed to monitor built environments, buildings and infrastructure, facilities and equipment, and water network. The accuracy and efficiency of digital twinning determine whether DT can be widely used, and the timely and continuous updating of information from the physical parts is vital for monitoring.

The second category of the research clusters is "analysis", which focuses on analysis using virtual parts after collecting data, including analysis, diagnosis and decision making. In the calculation and analysis sector, the existing applications of DTs can be classified into three categories. The first category is calculations and analysis of geometric information, which usually employs finite element methods to calculate and analyse with DTs. The second category focuses on calculations and analysis of non-geometric information, which is conducted based on sensors' monitoring data. The third level is the optimization and decision making based on the DT. The second category of application is the most common, and all of the three categories of applications remain at a relatively superficial level currently. Since a DT can provide high-fidelity digital replicas of the relevant entities in the real world, it has great potential benefits. First, individuals can study how to combine finite element methods and other methods with DTs to calculate and analyse digital 3D models. Second, most of the analysis, diagnosis and decision making are usually based on limited kinds of obtained data and limited kinds of indicators. Thus, the analysis and decision making is not comprehensive and objective enough. For further research, the analysis, diagnosis and decision-making process using DT should be better based on comprehensive data and indicators. Third, scholars and engineers should keep pace with new technologies and apply more advanced sensors to realize comprehensive monitoring, calculations and analysis of assets while considering more complex factors together instead of simple monitoring. Fourth, based on the DT, more application scenarios and demands should be proposed and more algorithms need to be developed to realize more complex and meaningful analysis, diagnosis, decision-making and even prognosis and prediction. Big data, AI, 3S technology, advanced sensors and other new technologies should be utilized as much as possible.

The third category of the research clusters is "action", which not only focuses on collecting data from the physical parts to the virtual parts, but also focuses on doing something with the physical parts using virtual parts, including automatic control and retrofitting and demolishing. Automatic control is an advanced level of O&M DT applications. In this sector, many goals are accomplished by monitoring and analysing, controlling and managing the physical parts, and conducting actions in the real world. In this type of application, actuators are usually employed. In addition, at the retrofit and demolishing stage, a DT is an essential tool to some extent. The first reason is that many existing old projects were built without many digital means. When conducting projects like retrofitting, demolishing, reconstruction and extension, existing data cannot be found from old target projects, and these projects are too challenging to be conducted without digital data for existing projects. Second, even though they can find some project data from related organizations, most of the data are pdf, doc, docx or even paper-based format, which are woefully insufficient for retrofitting and demolishing. Third, even if they find enough digital data on the existing project, the data are always out of date, which cannot promptly reflect the as-is project conditions. For example, if individuals want to conduct retrofitting or demolishing an old building, the as-is building is no longer the same a the designed or as-built drawings due to the construction deviation, foundation settlement, peeling, cracks and other defects. Without a DT, the correct elevations of the building’s edge cannot be fitted. Thus, they cannot conduct retrofitting or demolishing very well. In this field, DT can promptly make a digital replica for as-is projects to assist in retrofitting or demolishing old projects. The problem is still how to make the DT replica efficiently and accurately for the as-is old projects.

Finally, by leveraging all of the technologies mentioned above, it is possible to realize comprehensive asset O&M, such as infrastructure O&M, disaster prevention and mitigation. Similarly, the difficulties at the O&M stage usually emerge during the modelling phase, and the fusion of physical parts and virtual parts using connection technologies is also a challenging problem that should be focused on.

5 Conclusions

Based on a review of 134 articles related to DT in the civil engineering sector and another 27 influential articles related to the definition of the DT, BIM and CPS, we point out an appropriate definition for the DT and differentiate a DT from BIM and CPS mainly based on the as-is physical part, virtual model, connections between physical and virtual models, and the twin relationship between the physical part and the virtual model. In the civil engineering industry, DT, BIM and CPS have many similarities and distinctions. The three technologies are not mutually exclusive, and they can promote civil engineering digitalization together. According to the current research, a DT can be applied to buildings, cultural heritage, infrastructure, facilities and equipment, hydraulic engineering, and construction sites from the physical part perspective. From the virtual part perspective, a large amount of modelling, simulation, calculation and analysis software and advanced algorithms are employed in digital twinning. From the connection and data perspective, a DT can build the bridge between the physical parts and virtual parts by obtaining many types of data, such as point clouds, images, sensor data and other data, by leveraging various technologies and tools, such as laser scans, sensors, digital image processing, and mobile devices, to update geometric and non-geometric information on virtual parts to reflect physical parts in time. Various types of applications of DTs in civil engineering are systematically discussed from the service perspective, namely DT creation, design, construction, and O&M.

Based on the existing research, in this article, some thinking and suggestions related to DTs in the civil engineering sector are proposed. First, there should be a focus on developing algorithms and tools for digital twinning since the virtual part is the foundation of DT's applications. Second, DT can provide digital replicas for related existing projects, environment and surroundings to assist in design. Third, the DT can promote the development of smart construction. Fourth, DT plays an important role in defect detection and asset monitoring, and how to realize the fusion of physical parts and virtual parts using advanced connection technologies should be studied. Fifth, the DT must be deeply applied to calculation, analysis, optimization and decision making while using various technologies. Sixth, a DT is an efficient tool for automatic control, retrofitting, reconstructing and demolishing. Finally, with the development of AI, 5G, sensors, IoT, blockchain, software, and hardware, digital twinning in civil engineering will soon reach a higher level.

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