Digital Twin enhanced BIM to shape full life cycle digital transformation for bridge engineering: a comprehensive review

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Abstract: BIM has been playing a pivotal role during the last decade in bringing in revolutionary and systematic changes, especially for design and construction stages in bridge engineering; while the emerging Digital Twin (DT) technology, mainly applied in the operation and maintenance phases, has great potential to shape a DT-enhanced BIM framework to fully enable whole life cycle digital construction. However, the current adoption of DT in bridge engineering causes conceptual and technical confusion, which hinders the technology fusion to achieve its full potential. This paper aims at filling the gap by conceptualizing a DT-enhanced BIM framework from the perspective of bridge engineering. In total, 123 documents on BIM and DT were reviewed, compared, and analyzed; a crucial metrics-based performance hierarchy for bridge digital twin was concluded and a DT-enhanced BIM framework was proposed to promote full lifecycle digital bridge engineering implementation. Furthermore, the analysis and conceptual development align well with the existing mature BIM framework and are expected to contribute actively to the future development of BIM and DT and their integrated advanced technologies.

Keywords: Bridge Engineering; Digital Transformation; Digital Twin; Full Lifecycle, DT enhanced BIM, BIM 3.0.

1. Introduction

The revolutionary Building Information Modeling (BIM) not only can be regarded as a virtual model or software but also as a process of creating semantically rich information used for bridge engineering. BIM is an effective information management and technology integration platform[1], it can collect and manage bridge lifecycle information in a standardized and digital way, e.g. Common Data Environment (CDE); Industry Foundation Class (IFC) has been established as internationally adopted open BIM ISO standard. All of these have proved that BIM is worthy of continuous development to release its full potential. Similar to other application areas, BIM has advanced bridge engineering beginning from design and construction phases, e.g. its preplanning and design, 3D parametric modelling, collaborative design, clash detection, nD modelling and visualization, quantification, costing, and data management capabilities, which have significantly improved the efficiency and productivity, and BIM has therefore become a well-established tool for bridge design and construction management. As the adoption of BIM grows, there is a need to overcome more challenges to cover the operational phase, where intensive data and information have been collected, but often are incomplete, outdated, or fragmented [1]; while the current major use of BIM for bridge operation focuses on storing and visualizing bridge operation data[2], it lacks means to go deeper for data and knowledge mining for better decision to provide additional value for bridge maintenance [3,4].

The emerging Digital Twin (DT) technology has great potential to shape a DT-enhanced BIM framework to enable the whole life cycle digital transformation for bridge engineering. The DT can be used to replicate existing bridges in operation and maintenance phase (O&M) into their virtual twin models, constructing and updating these models based on multiple sources of data, and adding new functions to simulate different operation scenarios. Many scholars have discovered the potential of combining DT with BIM [3,5–8]. For example, Sun and Liu [5] proposed a novel hybrid model of Digital Twin-Building Information Modeling (DT-BIM) to manage resources. This model identifies the shortage of resources, analyzes requirements, performs decisions, dispatches the resources, and updates all the processes in the database with the support of AI. Boje [6] elaborates on ways of shifting from BIM with its existing domain knowledge and specific technologies towards DT to leverage more on the integration of IoT and AI through semantic models. This can help to address the challenge of changing from static, closed data with recursive interoperability issues towards a linked data paradigm, where the building product can be fully represented as a DT.

These studies show the critical value of combining BIM with DT, but the conceptual relationship between BIM and DT has not been clearly defined yet. BIM by now is well established and numerous standards, framework and application technologies have been defined / applied in a flexible and extensible way. For example, from the definition of BIM3.0A-BIM3.0D, it indicates that new technologies can be continuously adopted to enhance BIM. Currently there is no clear framework for data sharing, information interaction, and process integration among different stages to orchestrate DT into BIM framework. The concept of DT was originated from other domains, its current application in bridge engineering is still in its infancy, and a review of existing studies reveals that Bridge DT suffers from conceptual and systematic confusion. For example, Lin et al. [7] implemented a design document-based Finite Element Modeling (FEM) with real-time measurement data and defined the updated FEM as a DT model. Lu and Brilakis [8] achieved automatic model fitting by proposing a new method for processing point cloud data and described the point cloud model as a DT. Kang et al.[9] developed multiple surrogate models based on bridge monitoring information and defined that as a FEM-DT model to predict bridge repair schedule. These developments indicate a mixture of different DT definitions, making DT a product of technology stacking, hence difficult to form a unified digital process, data structure and standards, and seamless technology integration.

To address these existing gaps, this paper presents a comprehensive review with a aim to classify Bridge DTs according to their maturity and functional differences to avoid confusion and propose an ideal Bridge DT framework to fully exploit the value of DT technology in the bridge engineering field. The clarification of DT definitions and their relationship with BIM also helps to shape a full life cycle digital approach for bridge or even the entire AEC/O (Architecture, Engineering and Construction / Operation) industry. The proposed theoretical framework integrates different current and future technologies together to connect design and construction phases covered by BIM with the operation phase covered by DT, along with detailed full life cycle data share, information interoperability, process integration, and the conceptual relationship between BIM and DT. The main contents of the paper include (1) review and summarize the developments of BIM, digital twin, and BIM-DT respectively, and discuss the needs of BIM&DT (Section 3); (2) define an ideal Bridge DT along with concepts, classifications and technologies fusion (Section 4); (3) propose a DT enhanced BIM framework (Section 5).

2. Methodology

The research presented in this paper leverages a systematic approach, beginning with clearly defined objectives, followed by processes to seek answers for defined problems, and finished with a proposed framework. Three guiding questions are defined as follows:

(1) What are the applications and technical / conceptual gaps of the current BIM in addressing the whole life cycle bridge engineering?

(2) What are the latest research advances in DTs? What are the issues and status of DT research, especially in the field of bridge engineering? What are the existing DT definitions, classifications, and the underlying main characteristics and key performance indicators(KPIs) used for DT definition?

(3) What are the theoretical logic links between BIM & DT? and what are the gaps in the research of BIM combining with DT?

The review method used in this paper is shown in Figure 1, which illustrates the inclusion and exclusion criteria in the literature screening process. First, the Web of Science is chosen as the target database. Then, keywords were obtained in two ways, from research questions and keywords co-occurrence analysis, where the literature co-occurrence analysis was conducted using Citespaces software. The used keywords and references are shown in Table 1. The target literature were selected by their publishing year and abstracts, with a focus on high citation and Q1 and Q2 literature.

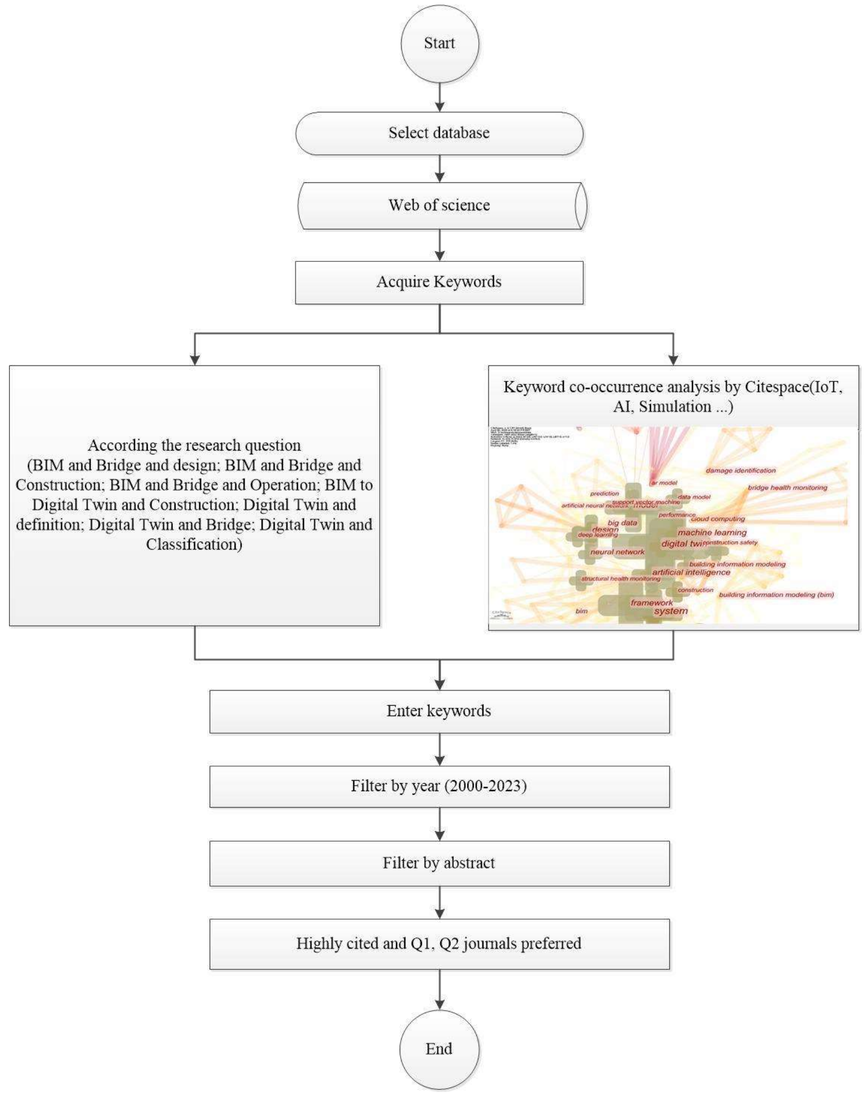

Fig 1. Methodology diagram

Table 1. Keywords and reference

Keywords	Reference
"BIM and Bridge and design"	[10–13]
"BIM and Bridge and Construction"	[4,11,14–19]
"BIM and Bridge and Operation"	[1,2,4,15–33]
"BIM to Digital Twin and Construction"	[2,5,34]
"Digital Twin and definition"	[35–37]
"Digital Twin and Bridge"	[8,9,38–46]
"Digital Twin and Classification"	[35–37,47,48]
"Digital Twin and IoT or BigData or AI or Simulation or Clouding Computing or Knowledge Graph or VR or AR"	[49–69]

3. Background

3.1. *Review of BIM*

The research background of BIM is profound, and this review summarized the major events of BIM between the 1970s and 2020, as shown in Table 2. According to the Web of Science database, the research of BIM in the field of bridges started around 2011[26], and many bridge management systems (BMS) based on BIM have been developed to provide decision support throughout the design, construction, operation and management phases. The state-of-the-art BIM in the whole life cycle of bridges is presented as follows.

Table 2. BIM big event schedule

Time	Big Event
1970s	The BIM concept was introduced in 1970 by Professor Charles M. Eastma. [70].
2000s	The concept of BIM was introduced in the construction industry.[71]
The 2001 year	ISO began preparing the 12006 standards on building information[72].
The 2003 year	The US Federal General Services Administration (GSA) has launched the 3D-4D-BIM program. [72]
The 2004-2006 year	Autodesk's Revit-based BIM products have begun to roll out to the global market.[72]
The 2007 year	The BIM concept was introduced in 1970 by Professor Charles M. Eastma. [72]
The 2007-2012 year	Autodesk enhanced modeling software Revit and multiple acquisitions with modeling software, including Robobat, Ecotect, Horizontal Glue, and Qontext. [72]
The 2016 year	Mainly promote Open BIM, "use model" to "use data."[72]
The 2020 year	Continue to practice BIM 3D models, innovate mathematical models, and practice. [72]

3.1.1. *BIM in Bridge Design Phase*

The application of BIM in the bridge design phase is reflected in parametric modeling, design clash detection , collaborative design, and overall structural safety checking [11,12]. Regarding parametric modeling, BIM is most widely used in constructing three-dimensional (3D) objects from two-dimensional (2D) drawings. The creation of such 3D models can provide a perfect digital and graphical representation based on design results [22]. Through the parameterization of main components of conventional standardized bridges, and entire bridge models can be created quickly with high accuracy and efficiency [10] BIM technology can also be used to build a standardized database for 3D bridge components, such as box girders, piers, and foundations. For bridge line design, parametric modelling based on the original foundation materials and line design resources, the full line design for approach and main bridge can be automatically completed [13]. Furthermore, the Bridge Information Modeling (BrIM) concept has been developed based on BIM to enable full digital design for bridges [23]. The New York State Department of Transportation (NYSDOT) implemented their first “model-based contract”, with intelligent 3D bridge models playing a central role. This approach minimizes paper plans, requires project bidders using digital copies of terrain, geotechnical, and road 3D model of the entire project [24]. Bentley’s OpenBridge solution eliminates multiple data entries from different end-users with different disciplines and unifies the data in a single source of truth, a digital 3D model. This 3D model is a live model that can be updated to reflect real-world bridge conditions as the bridge lifecycle progresses[73].

In terms of design collision detection, this includes collision detection of the reinforcement and prestressing steel in the design process, collision detection of the facilities in the bridge and tunnel electromechanical pipelines, and interference detection of the other components in the design[22]. In collaborative design respect, a BIM coordinated design system can integrate designers into a unified collaborative design system through the professional division of labor to improve the efficiency of bridge design information flow[74]. In addition, a BIM coordinated design system can manage the whole design process and get integrated with other information management systems to establish an integrated and informative design management structure. For bridge structural analysis and checking, 3D structural models can be generated first through parametric modeling and later get imported into downstream software for design calculation, then further into the finite element analysis software to get corrected based on the numerical analysis results [13]. In addition, this 3D BIM approach can help to streamline processes to include the nonlinear analysis of various types of bridges, the simulation of vehicle loads, pre-stress, shrinkage, creep, temperature load analysis, and the nonlinear simulation of the construction and completion phases [13].

3.1.2. *BIM in bridge construction phase*

Building bridges is a complex and dynamic process, especially for medium and large size bridges. As construction progresses, the scale and complexity of the project grow correspondingly, as does the difficulty of construction management [69]. Currently, BIM technology can help to complete the pre-construction collision check, in-depth design and virtual construction during the construction process all together [68].

Specifically, on the one hand, for pre-construction BIM applications for road and bridge projects, 3D visualization techniques are used to perform construction aids such as collision checking and detailed design. In existing construction drawings, specialized components are separated from each other, and the complexity of road and bridge construction makes it difficult to detect potential pipe collisions. The use of BIM can match each component with the corresponding parameter-driven information. The 3D model is checked for collisions, the number of clashes with details are automatically displayed, and a collision detection report is issued to correct errors and save time. In addition to components checking, BIM can also detect collisions between machines, workspaces, and structures during the construction process; to support traffic flow analysis, calculate performance parameters such as structural stability and load-bearing capacity, and to allow for continuous full and partial detailing processes. This helps to reduce construction costs, mitigate risks, and ensure construction quality. On the other hand, through BIM based schedule simulation, post-construction quality inspection, and disaster emergency response, the whole process of bridge construction is centralized on an information-sharing platform to predict possible problems during construction in advance and to develop measures to improve the efficiency and level of construction management.

As the demand for bridge monitoring and management increases, the functionality of BIM is being expanded from 3D BIM to 6D BIM. For example, 4D BIM with time as the fourth dimension [14] and 5D BIM with cost as the fifth dimension[15]. Kaewunruen et al. [16]combined 3D modeling with schedule, cost estimation, and carbon footprint analysis throughout the full life cycle of a bridge project to construct 6D BIM. Additionally, Zhang et al. [17]presented an innovative approach to integrate BIM and expert systems to address deficiencies in construction's traditional safety risk identification process. Zou et al. [18] focused on bridge projects and proposed a new method for risk visualization and information management by integrating a bridge project’s risk breakdown structure into a 3D/4D BIM and establishing a linkage between the risk data and the BIM. Zhu and Contreras-Nieto et al. [19,25]integrated BIM with a geographic information system (GIS) that contained information management, inspection management, and technical condition evaluation, enabling users to cooperate. In addition, with the advancement of the green bridge concept, Nahangi et al. [71] used BIM to quantify the implied greenhouse gas (GHG) emission content in a bridge by recording the number of materials and the energy collected on-site during pre-construction preparation and construction for GHG assessment.

3.1.3. *BIM in Bridge operation and maintenance phase*

Due to the long lifetime of bridges, BrIM is often used on the historic bridges[75]. The objective of modeling a bridge is to generate a digital model that records information to allow the cultural significance of the bridge to be preserved while ensuring its safe operation and to provide a virtual tool to help determine effective remediation strategies [78]. Jeong et al.[26] developed a framework to integrate BrIM and SHM (Structural Health Monitoring) for enhanced monitoring of bridges by using OpenBrIM standards to receive, store, and analyze the data captured through sensors.

SHM system via sensors and visual inspections can produce the primary data source for bridges. The manual based inspections are risky, challenging, and require working in unsafe conditions such as post-disasters. Thus UAVs, radar, point cloud scanning, photography, and other equipment are gradually used for bridge inspection. The gradual popularization of bridge sensing equipment and inspection equipment has brought new changes to data acquisition, mining and the use of multi-source data.

To meet the growing demand for bridge management and maintenance, new technologies are integrated with BIM, such as numerical analysis, 3D scanning, AR/VR/MR, and other functions based on BIM, to overcome these challenges, as shown in Figure 2, which have facilitated the development of BIM to DTs.

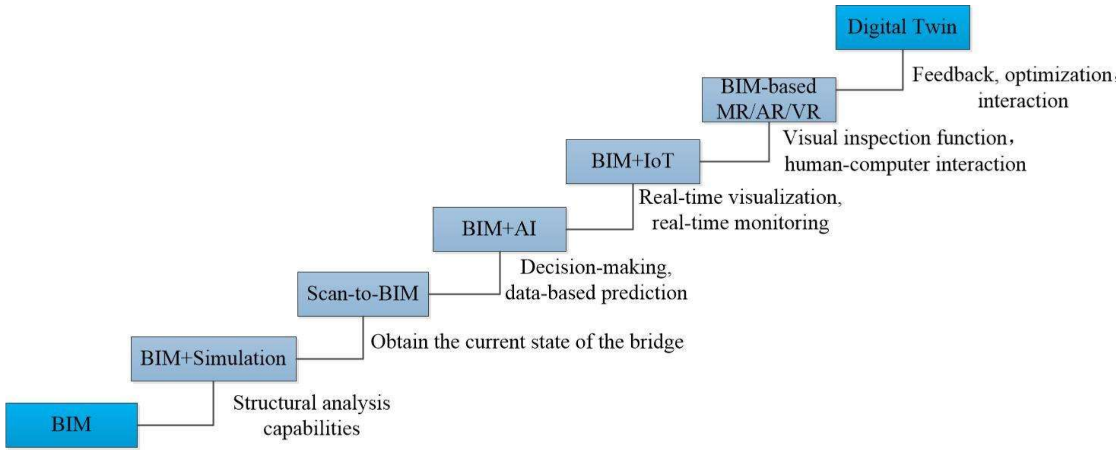

Fig. 2. Evolution of BIM to digital twin in bridge engineering

In a BIM-supported simulation, integrating BIM and FEM allows for the complex monitoring of a structure throughout the bridge life cycle, significantly improving the efficiency of bridge management[76]. For example, Zhang et al. [27]presented a parametric modeling method of Revit software to set up a corrugated steel web continuous girder bridge model. They utilized Dynamo visual programming software to retrieve the geometric parameter information of the BIM model. They converted between the BIM model and FEM with Python language programming to endow the BIM model with mechanical properties. Chen et al. [28] established a BIM-based parametric pre-processing model of ship, wharf, and collision avoidance facilities, opened the interface of ABAQUS to transform a model and complete the collision analysis of a ship and a bridge under various working conditions and returned the analysis results to the BIM model for unified integration. BIM parametric technology linking with FEM can improve the efficiency of multi-conditions sensitivity analysis to achieve the effect of dynamic visual adjustment.

Due to the different between the design conditions and as-built condition, it isn’t easy to implement BIM for existing structures. The scan-to-BIM process is complicated for bridge structure design parameters automatically to reduce time and resources [29].For example, Wang et al. [30] proposed the automatic prediction of concrete bridge deck slab dimensions based on 3D scanning technology and stored this prediction in an as-built BIM. Experimental results show that the proposed technique can accurately and efficiently estimate the dimensions of full-scale precast concrete bridge deck panel with an accuracy of 3mm and automatically create as-built BIM models of the panels.

BIM-combined AI is often used in data mining techniques to perform anomaly detection that relies on pattern recognition to cluster normal and abnormal bridge behaviors and thereby detect abnormal behavior when the threshold between cluster classifications is exceeded [77]. Tae et al. [2]used an artificial neural network based on structural analysis theory and trained with long-term sensing data in an IFC-BIM environment; they proved the prediction accuracy of the proposed ANN model under complex loading conditions and its ability to identify element anomalies for maintenance.

Regarding BIM-based Mixed Reality, Nguyen et al. [31]developed a BIM-based bridge inspection and maintenance model on an MR platform based on Microsoft HoloLens, which addressed the ineffective decision-making process on maintenance tasks from the conventional method which relies on documents and 2D drawings on visual inspection.

For BIM and the IoT, Scianna et al. [32]proposed the strength of an IoT system connected to a BIM model that was developed to allow the real model to be connected to the BIM model in real-time by using a database management system to which the data detected using the sensors were transmitted, thus enabling the risk assessment of the real structure. Panah et al.[33] combined BIM with traditional bridge health monitoring to develop a bridge monitoring system that could organize and visualize a large amount of sensor data and subsequent health information over a long period.

In summary, the introduction of these new technologies has gradually equipped BIM with the ability to process large amounts of data from multiple sources, the ability to mine the data, and the additional ability to provide feedback to users, such as prediction and decision-making. This process has led to the development of BIM towards the DT.

3.2. *Review of BIM&DT*

It can be concluded that although the application of BIM in bridge engineering has covered the whole life cycle, there are still limitations in dynamic real-time and multi-source data management, data mining, and function expansion of BIM [78]. Therefore, it is necessary to feed into new advanced technology in BIM to compensate for the shortage of BIM in the whole-life cycle of bridge management. Fortunately, the ability of DT technology to fuse multiple technologies to achieve the surface reconstruction of existing bridges can compensate for the difficulty of modeling old bridges due to the unavailability of information. At the same time, real-time data processing and mining capability can tackle the problem of massive sensing data processing and application. Meanwhile, relying on the information integration capability and standard data circulation capability of BIM platforms, such as IFC, it will facilitate the realization of the ideal bridge DT.

Many scholars have discovered the potential of combining DT with BIM [3,5–8]; The concept of using BIM to develop DT has also been widely pursued in the construction industry [3]. For example, Sun and Liu[5] proposed a novel hybrid model of Digital Twin-Building Information Modeling (DT-BIM). This model identifies the shortage of resources, analyzes the requirement, performs decisions, dispatches the resources, and updates all the processes in the database with the support of AI. Tan et al. [79]combine the advantages of computer vision and DT to combine lighting and monitoring to create a Digital Twining Lighting (DTL) platform that leverages the ability of BIM to fuse heterogeneous data from multiple sources to improve indoor energy efficiency in smart buildings. Levine and Spencer[80] proposed a DT framework for post-earthquake building evaluation that integrates unmanned aerial vehicle (UAV) imagery, component identification, and damage evaluation using BIM as a reference platform. Alizadehsalehi and Yitmen [81] developed a generic framework of a DT-based automated construction progress monitoring using BIM, DTs, and XR for automatic construction progress monitoring. Zhao et al.[34] proposed a scan-to-BIM-based DT evaluation method for nearly zero-energy buildings retrofitting existing buildings, which evaluates the retrofitting scheme through comprehensive analyses of building energy consumption and building carbon emission indicators. A BIM energy model is created based on 3D laser scanning data of existing buildings.

In the combination of BIM and DT, BIM focuses on design and construction phases, while DT focuses on O&M phases. However, a combined framework for BIM&DT is missing in this process to enable full life cycle data-sharing process and the seamless integration and interaction of various technologies. Specifically, developing a BIM &DT framework in the bridge engineering domain must address two key issues. On the one hand, data from the design and construction phases do not automatically flow to the O&M phases, so it is difficult for these data to be used to support maintenance decisions, which leads to a decrease in data value and an increase in circulation costs [25]. On the other hand, the development of BIM&DT should not be based on stacking techniques without synergy. Multiple models based on various data sources should be created, and interaction between models should be realized.

3.3. *Review of digital twin in bridge engineering*

This section highlights the current state of research on DT in bridge engineering by reviewing DT-related papers from the Web of Science database. From the literature review, the implementation of DT for bridges is divided into three directions, as shown in Table 3. These are data-driven model updating, 3D scan-based surface model reconstruction, and BIM platform-based data integration.

Firstly, a data-driven approach to FEM updating can explore potential relationships between different datasets, quantify uncertainties, and make predictions for bridges in specific situations. For example, Kang et al. [9] use a large amount of data for training through intelligent algorithms and finally transform that into numerical model feature parameters. Then by changing these parameters of the original numerical model, a Bridge DT is obtained for bridge maintenance. Ghahari et al.[38] proposed a continuous Bayesian model updating technique by which linear/non-linear FEMs, including soil-structure interaction effects and foundation input motions, are jointly identified. The bridge created by this method makes the FEM closer to the actual bridge to a certain extent. However, it is difficult to obtain a visualization of bridge surface distress; besides, FEM-based model updates are often over-simplified, e.g. using linearity assumptions which can bias the output, with the problem of being simulated but unrealistic.

Secondly, the update method is based on 3D surface modeling, which allows for an intuitive update of the damage information for the model. Dang and Shim [82] used the point cloud scanning method to generate DT models of existing bridges, and the slice-based object fitting method makes the model more accurate. Building an automated, precise, and IFC-aligned 3D bridge model is considered as the main attribute of Bridge DT. Mohammadi et al. [39] found that the bridge point cloud model created by the new technique of terrestrial laser scanning (TLS) showed higher point density levels and more acceptable in-situ measurement protocols in terms of distribution, outlier noise levels, data integrity, surface bias, and geometric accuracy, and defined it as a DT model. However, this update model method lacks consideration and support for monitoring data (such as real-time bridge strain and acceleration). The empirical way of judging the actual condition of a solid object based on a 3D surface model cannot be used for data mining for implicit knowledge.

Finally, the integration and update methods based on the BIM platform can consider 3D models, FEM, and information integration management. Kaewunruen et al.[40] built a Bridge DT by integrating a bridge risk inspection model in a BIM platform, which is a more effective regarding the mitigation of risk and uncertainty in extreme weather conditions for all stakeholders.

In addation, DT is gradually used in bridge engineering projects. For example, the Second Ring Elevated DT Project in Chengdu, China, established a bridge component coding specification by giving each bridge component an ID number. This enables fast and accurate positioning of data objects. The bridge component "ID card" is marked into an aluminum plate with the component code and QR code attached to the bridge pier. The O&M workers only need to scan the QR code with a particular cell phone app, and they can get all the information about the pier and related components within 30s. Based on the BIM platform overlaid with GIS, the visualization of bridge data can be further improved and the real time bridge status can be achieved through the joint application of mobile and IoT. After a period of data accumulation and analysis, it was found that after using the DT, the damage treatment efficiency of the Second Ring elevated bridge was eight times faster than that of other bridges, and the productivity was increased by 8.3 times[83].

These advanced DT technologies can help to process multi-source of data, to facilitate the digital replication of physical bridges to some extent, making virtual bridges closer to real physical ones and improving decision-making accuracy. However, it should also be noted that there is still conceptual confusion in the current research for DT in bridge. Different concepts, tools and application examples are defined as DT, and that may lead to some un-coordinated technological developments, making BridgeDT [8][9]product of technology stacking, difficult to form a unified digital process, data structure, and data standards, hence hindering the formation of a collaborative effort. It therefore needs unified DT definitions, hierarchical concepts and framework, and levels of maturity and functionality to address the above issues.

Table 3 Bridge DT definition form

Bridge DT Definition Form	Reference
Updated finite element model	[7,9,38,41–44,84]
3D surface modeling	[8,39,85]
Model establishment and update based on the BIM platform	[40]

4. Classification and definition of bridge digital twin

Before presenting the developed BIM&DT framework for the full lifecycle management of bridges, the ideal Bridge DT concept is first defined and positioned to conclude the current study through a hierarchical format. This section starts from the reviewing DT concepts and applications in other related mature fields and summarizing the main features of DTs, then analyzes and extracts the existing KPIs on which the classification of DTs relies. At last, based on these works, a hierarchical ranking of Bridge DTs is performed to define the ideal BridgeDT.

4.1. *Summarize the characteristics of digital twin*

The DT concept was first proposed in 2002[47], it suggests that with the data of physical devices, a virtual entity and subsystem representing the physical device could be constructed in virtual (information) space and these connections between the virtual entity and subsystem representing the physical device were not unidirectional and static but instead linked together in the entire product life cycle.

DT characteristics can be captured from existing definitions especially from other mature domains as application areas and specific use case often characterize definitions of DTs. Currently, DT technology is most maturely applied in the fields of manufacturing (including smart design[86–89], management [90,91] and factory[92,93]), smart architecture[94–97] and cities[84,98].Critical features can therefore be summarized by comparing and mapping keywords from articles on DT definitions and concepts, as shown in Table 4. The application of DTs in smart cities [102,103] shows vital sensing and data transmission capabilities. In addition, AI is increasingly used in urban management and operational decision-making, from incarceration sentencing to city pension appropriation, surveillance, and infrastructure management. The real-time interaction capability of DTs is demonstrated in the study of Pan et al. [94]; they proposed a multi-level cloud computing-enabled DT system for the real-time monitor, decision, and control of a synchronized production logistics system. The study by Yi et al.[99] illustrates the characteristics of deep integration of DT; they proposed an application framework for DT-based smart assembly. Product assembly station components are detailed in the physical space layer; two main modules, communication connection and data processing are integrated into this framework. Shiqian Ke [100] and Oyekan et al. [91] show that DT can be highly capable of visual representation and human-computer interaction; for example, Shiqian Ke et al. [100] designed an enhanced interaction framework based on VR, AR, and MR in DT to promote interaction and fusion for DT technology between physical space and virtual space, then provide various manufacturing service. In sum, the features of the DT can be summarized as follows:

(1) Omni-directional sensing system. To replicate the real physical world, obtaining a full range of information from real-world senses such as vision, touch, and smell is necessary.

(2) Real-time interaction. The ultimate goal of DT technology is to reproduce the real physical world entirely, so the real-time interaction between the natural world and the twin world is significant. Interactive operation and two-way connection are required between the physical entity, the virtual model, and the twin model.

(3) Full integration. The whole process, full element, and full-service integration are needed to realize the DT process.

(4) High level virtual representation.

(5) AI function driven by data. To achieve intelligent decision-making, prediction, and early warning, data-driven machine learning, deep learning, ontology, and other technologies need to be embedded in a DT.

(6) Sharing, coordination, and cooperation. The DT platform does not exist internally and externally but with information sharing and collaborative operation.

Table 4 Different definitions of digital twin

Reference	Definition of DT	Keywords
Glaessgen Edward H, Stargel, D. S[47] (2012)	"An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin."	◆integrated
M Grieves [101](2014)	"Virtual representation of what has been produced."	◆Virtual representation
Stephan Weye., et al[102] (2016)	"One of the next big advances in modeling, simulation and optimization technology"	◆advances in modeling, simulation, and optimization
Rainer Stark[103] (2017)	"A DT is the digital representation of a unique asset (product, machine, service, product service system or another intangible asset) that compromises its properties, condition, and behavior employing models, information and data."	◆digital representation of an asset
Zhuang[104] (2018)	"Virtual, dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behavior, life, and performance in a timely fashion."	◆a dynamic model in the virtual world
Zhuan[104](2019)	"Digital representation of the physical asset which can communicate, coordinate and cooperate the manufacturing process for an improved productivity and efficiency through knowledge sharing."	◆knowledge sharing digital representation

4.2. *Analyze the Existing Digital Twin Classification*

Many researchers have identified specific terms to denote certain technology applications within particular dimensions. Analyzing the DT classification from different perspectives will assist in determining the KPIs for DT classification more clearly. The DT classification includes three main dimensions, maturity, life cycle, and function, which are reviewed separately. The KPIs are analyzed through classifying DTs in the existing literature following those three dimensions.

4.2.1. *Level of maturity*

The complexity or maturity of DT applications refers to the level of information and functionality generated using that data. Specifically, Julien and Martin [36] first classified a numerical representation by its maturity in five steps, including a Digital Mirror, Digital Shadow, Digital Twin, and Cognitive and Autonomous DTs. The first step in virtualization is a Digital Mirror, which includes a set of mathematical models, such as 3D simulations, that represent the physical objects and their behaviors. However, there is no direct communication between the physical and digital parts, and all information must pass through the user. A Digital Shadow represents all the digital activity of a physical object. It allows the dynamic representation of all changes in its physical counterpart to be tracked through one-way threads. The third step incorporates the physical and virtual parts into the cyber-physical system. The DT is the digital part of this system. Real-time communication is possible from the physical object to the DT system and from the DT system to provide the object with partial or full control feedback. DTs can be developed by adding predictive capabilities to cognitive systems. With more decision-making and control over the counterparts of DTs, this will become autonomous technology.

Kritzinger et al. [37]classified DTs into three classes: Digital Models (DMs), Digital Shadows (DSs), and DTs. In the DM stage, there is no automatic data exchange between a physical object and a digital object, the digital object does not fully describe the physical object, and all data exchange is done manually. DSs enable automatic unidirectional data flow between physical and digital objects, with changes in the physical object causing changes in the state of the digital object, but not vice versa. Furthermore, in the DT phase, there is a two-way automated data exchange between the physical and digital objects. Changes to the physical object can directly affect the digital object and vice versa.

Madni [35] defined four levels of sophistication: Pre-digital Twins, Digital Twins, Adaptive Digital Twins, and Intelligent Digital Twins. A Pre-digital twin is created before the physical prototype is designed to reduce technical risks and problems in pre-engineering. Once the physical entity has been made, the DT virtual model is created with the physical entity's performance, health, and maintenance data, which can be updated in bulk. An adaptive DT adds the virtual system model of the physical twin with an adaptive UI for the DT and enables real-time data from the physical entity to be updated for the virtual model. An intelligent DT improves on an adaptive DT by adding reinforcement learning through machine learning and helping real-time updates of physical and digital objects.

Oracle [105] classified the applications of IoT DTs into three classes: virtual twins, predictive twins, and twin projections. In a virtual twin, Oracle’s Device Virtualization feature creates a digital representation of a physical device or asset in the cloud. The virtual twin uses a JSON-based model with observed and expected attributes such as weight, altitude, and length and a semantic model. In predictive twins, DTs are implemented using machine learning techniques to build an analytical or statistical model for prediction. It is not necessary to involve the original designer of the machine. This differs from physics-based models, which are static and complex, do not adapt to changing environments, and can only be created by the machine's original designer. In Twin Projections, forecasts and insights are integrated with back-end business processes, making IoT an integral part of business processes.

Based on the above, six KPIs-based maturities are extracted from articles [35–37,105] that classified DT levels according to maturity, as shown in Table 5.

Table 5 KPIs for classification DT

KPIs for digital twin classification	References
Data flow direction (one-way or two-way)	[36,37]
Data flow method (automatic or manual)	[36,37]
Data quality (Sample, Moderate, Complex)	[35,105]
Update speed	[35,105]
Cognitive ability (Predication, Decision Making)	[35,36,105]
Visualization interface	[35]

4.2.2. *Level of lifecycle phase*

Trauer et al. [106]proposed three sub-concepts of DT based on the life cycle, namely the Engineering Twin, Production Twin, and Operation Twin. Tharma et al. [107]divided DT into three phases according to their lifecycle stages and the scope of the data. The digital model includes all documents and models from the start of the product launch, including all product variants. The production twin contains all information about the manufacture of a specific product. The operation twin narrows down the data to that required for the operation.

4.2.3. *Level of function use*

According to their function, DTs are classified as design, system integration, diagnostics, and prediction DTs[108]. For design DTs, simulation and visualization during the design phase can verify and check the overall 3D design and ensure that all components fit together. For system integration DTs, 3D visualization at the system level can verify constraints such as spatial footprints and physical connections. Interactions can be simulated by connecting to DTs of other components, including data transfer and control functions, mechanical and electrical behavior, and hypothetical situations. Observing a DT, such as in 3D visualization, for diagnostics, DTs can support troubleshooting. Virtual reality glasses can provide field technicians with visualizing parameters overlaid on actual equipment. Simulations can add unobservable data, such as untouchable components' temperature or material stresses. For prediction DTs, past and present operational and sensor data combined with predictive algorithms provide insight into the condition of the equipment and the likelihood of different failure modes. For advanced services DTs, if all advanced service parameters (such as IoT connectivity and analytics algorithms) are pre-configured in the DT, they can be enabled when the equipment is installed and the customer orders these services. In the best-case scenario, no further engineering is required.

4.3. *Classify the bridge digital twin*

This section discusses the classification of Bridge DT according to two aspects: KPIs concluded in Section 4.2 and functional requirements of DT in bridge engineering. Pre- Bridge DT and Ideal-Bridge DT are used to divide Bridge DT into two levels, as shown in Figure 3. The implementation details for these two levels are shown as follows:

Classifiction	Pre-BridgeDT	Ideal-BridgeDT
KPIs		
1.Data flow direction (1-1 One-way, 1-2 Two-way)	1-2	1-2
2.Data flow method (2-1 Semi-automatic, 2-2 Automatic)	2-1	2-2
3.Data quality (3-1 Sample, 3-2 Moderate, 3-3 Complex)	3-2	3-3
4.Update speed (4-1 Regular updates, 4-2 Real-time updates)	4-1	4-2
5.Cognitive ability (5-1 Partial, 5-2 Complete)	5-1	4-2
6.Visualization interface(6-1 Partially display, 6-2 Full visualization)	6-1	6-2
Functions × None; ● Part; √ All		
Modeling	√	√
Simulation	√	√
Update Model	●	√
Integration Model	●	√
Surface Reproduction	●	√
Feedback (Assement, Prediction, Decision-making)	●	√
Automatic Control	×	√

Fig. 3. 2 levels of Bridge DT definition according to KPIs and functions

4.3.1. *Pre-Bridge DT*

In Pre-Bridge DT, partial automation modeling can be completed by collecting more information, such as real-time bridge monitoring and inspection. As shown in Figure 4, the data flow is still a single flow, and changes in the physical bridge will directly affect the digital model and vice versa. There is incomplete model integration, model updates for non-real-time models, and partial feedback functionality.

In practical applications, this can be reflected as the integration of the actual bridge surface damage model obtained with point cloud scanning based on a BIM 3D model or as the establishment of a data-driven bridge surrogate model based on dynamic monitoring information to achieve the updata of the FEM.

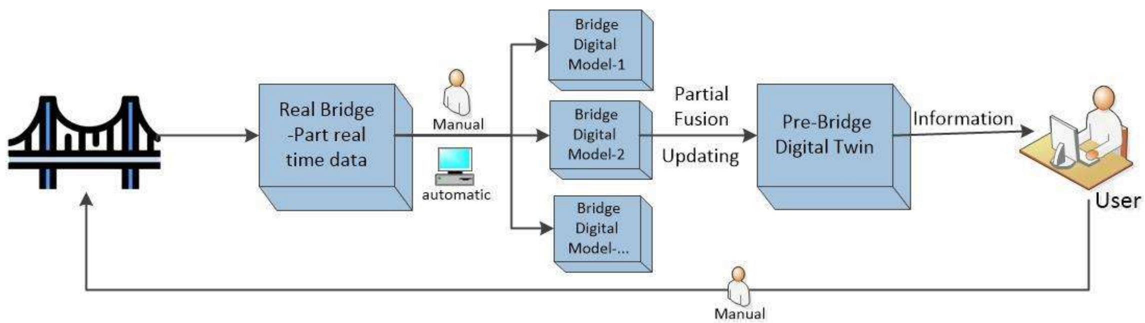

Fig.4. Pre-Bridge DT

4.3.2. *Ideal-Bridge DT*

The Ideal-Bridge DT is to leverage comprehensive, multi-dimensional, high-quality bridge information to automate real-time bridge model updates and complete integrated model integration for joint feedback. As shown in Figure 5, data flows in both directions to transform physical bridges. It can influence the digital model in real-time and obtain collaborative feedback or even automated control.

In practice, a full range of sensors are used to obtain the bridge condition data and the surrounding environment data, which are processed, classified, transmitted, and updated to the DT platform, which integrates the bridge surface model, structural model, information model, and surrogate model to present the actual state of the bridge surface, the mechanical condition of the bridge structure, the bridge history, and the prediction of the future state, respectively.

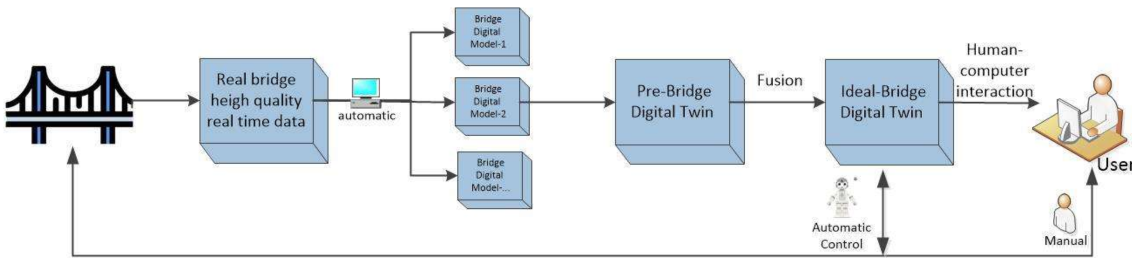

Fig. 5. Ideal-Bridge DT

After completing the hierarchy of Bridge DT, the existing research is positioned in this hierarchy, as shown in Table 6. Also, Table 6 shows the KPIs achieved by the current studies on the DT of bridges and as long their functionality.

Table 6 Assessment of existing research on the digital twin of bridges

Reference	KPIs	Function	Classification
1.Kang J [9]	1-2, 2-1, 3-2,4-1	Update model, Assessment	Pre-Bridge DT
2.Lin K [7]	2-1,3-2,4-1	Update model	Pre-Bridge DT
3.Hyoung [109]	3-2	Update model	Pre-Bridge DT
4.Ye S[110]	2-1, 3-2, 4-1	Update model	Pre-Bridge DT
5.Shim, Chang-Su [11]	1-2, 2-1, 3-2, 4-1	Update model Assessment	Pre-Bridge DT
6.Farid [38]	2-1, 3-2, 4-1	Update model	Pre-Bridge DT
7. Jiang [42]	3-2, 4-1	Update model	Pre-Bridge DT
8.T.G. Ritto, F.A. Rochinha[43]	1-2, 2-1, 3-2, 5-1, 6-1	Integration model Decision making	Pre-Bridge DT
9. Lu R [8]	2-1, 3-2, 4-1	Surface reproduction	Pre-Bridge DT
10.Shao S[85]	3-2,6-2	Update model	Pre-Bridge DT
11.Kaewunruen S [40]	1-2, 2-1,5-1	Integration model Decision making	Pre-Bridge DT
12.Masoud Mohammadi[39]	2-1, 3-2, 4-1	Surface reproduction	Pre-Bridge DT
13.Sakdirat Kaewunruen[40]	3-2, 5-1, 6-1	Integration model Decision making	Pre-Bridge DT

KPIs: 1. Data flow direction (1-1 one-way,1-2 two-way); 2. Data flow method (2-1 Semi-automatic, 2-3 automatic); 3. Data quality (3-1 Sample,3-2 Moderate, 3-3Complex); 4. Update speed (4-1 Regular updates, 4-2 Real-time updates); 5. Cognitive ability (5-1Partial,5-2 Complete)6.Visualization interface (6-1 Partially integrated display, 6-3 Full content visualization)

4.4. *The Ideal-Bridge Digital Twin*

The KPIs and functions that an ideal Bridge DT should have and the state of the application in practice are described in Section 4.3; This section analyzes the ideal Bridge DT regarding the five-dimensional framework proposed by Tao, et al. [111]. As shown in Figure 6, it includes the physical entities, data, Bridge DT virtual models, users, and connections. The main functions of each part are as follows.

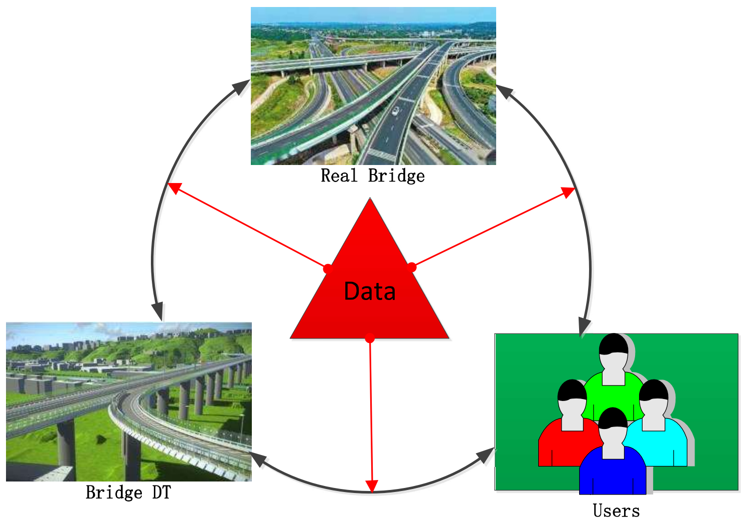

Fig. 6. Important components of Bridge DT

(1) The bridge physical entity is the ultimate service object of Bridge DT and the primary data source. The bridge entity can be divided into components and units according to structure and function in obtaining bridge data. For example, the entire bridge has a massive amount of information and various types of long-span cable-stayed bridges. Therefore, towers, beams, piers, cables, and other components can be separately labeled for management. It is also possible to divide the beam's subunits according to the bridge's length and position to monitor, analyze, predict, and maintain a single component or subunit. The overall analysis can be done for the entire bridge state by establishing constraints and coupling relationships between elements or units.

(2) Data is the core of a DT, flowing between the physical entity, the user, and the DT model. The specific data content is shown in Table 7.

Table 7. Data content

Transfer object	Data content
Real bridge ---Bridge DT	◆Bridge monitoring data, stress and strain, bridge disease information; ◆Comprehensive data on the surrounding environment, such as temperature, wind speed, wind direction, and extreme weather; ◆cracks, corrosion; ◆Traffic Information.
Bridge DT----User	◆Bridge status information; ◆Perdition information; ◆Maintenance plan advice; ◆Emergency handling; ◆Decision-making assistance, etc.
User--- Real bridge	◆Maintenance measure; ◆Traffic adjustment and other efforts.

(3) The Bridge DT virtual model is the engine of the DT. The virtual model fully uses the data obtained from the physical entity and outputs the feedback information that serves the user and the physical bridge. According to the bridge design, construction, and operation requirements, Bridge DT is composed of a 3D physical model, finite element analysis model, data-driven surrogate model, and information management model. The functions of the four models are shown in Figure 7.

(4) The user is the operator of the DT platform and, at the same time, the ultimate manager of the bridge.

(5) The connection method determines the direction of data flow, the degree of automation, and the degree of real-time.

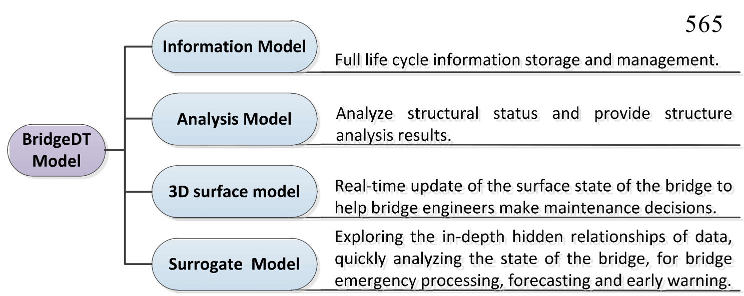

Fig. 7. The components and function of Bridge DT

5. The Proposed Framework of Digital Twin enhanced BIM

5.1. *DT enhanced the BIM framework in the bridges*

Based on the significant amount of reviewed papers and intensive analysis, a DT-enhanced BIM framework is proposed (Figure 8), it aims at enabling the data flow throughout the whole life cycle of bridges. The framework includes three perspectives, (1) the life cycle process, (2) the function and implementation process, and (3) concept evolution, details are concluded as follows.

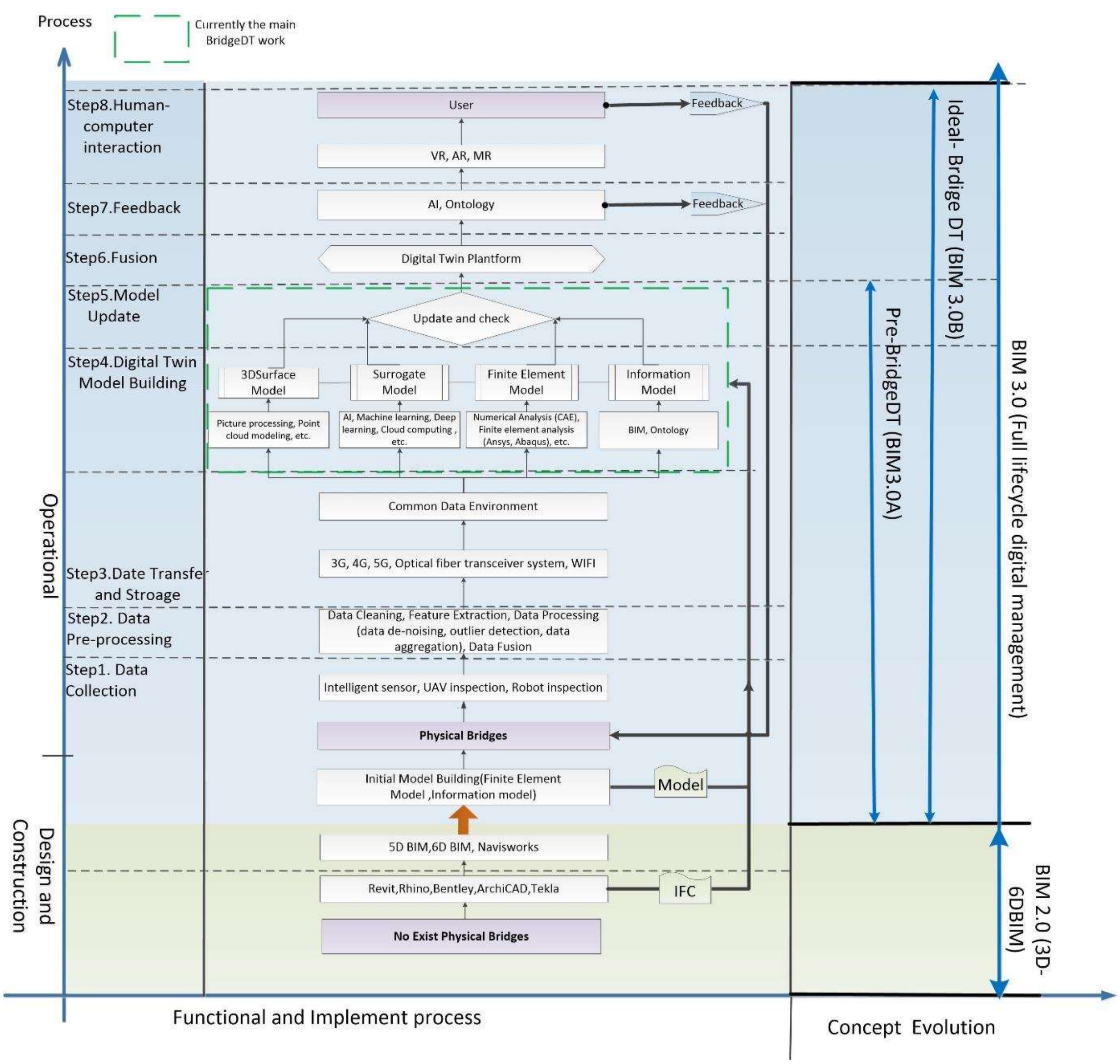

Fig. 8. A DT-enhanced BIM framework for bridge engineering

5.2. *Life Cycle Process*

From the bridge life cycle perspective, BIM mainly contributes to the design and construction phase, while DT technology is mostly used for O&M phase. The information from the design and construction phases is used again in the operation phase in the form of IFC files and 3D models, and the models are updated on the original model, as shown in Fig. 8. At the same time, DT information management will rely on BIM during the bridge operation phase. Therefore, in the proposed framework DT will link design and construction BIM information models and feed for bridge operational information management to integrate the entire bridge life cycle together.

5.3. *Function and Implementation Process*

Since the functions and applications of BIM in the design and construction phases of bridges are well-developed and described in detail in section 3.1, this framework focuses on the functional processes and implementation of DT technology in bridges' O&M phases.

There are eight processes defined for Ideal-Bridge DT, which cover a range of techniques from the construction of physical entities to the interaction of physical and virtual entities. For the implement process, many technologies and tools are listed to support the realization of the corresponding function. Technologies and tools involved in the O&M phase of DT are defined from three perspectives, namely (1) data collection, transmission, and share; (2) data applications; (3) data visualization and mining.

5.3.1. *Data collection, transmission, and share*

IoT is mainly used in the bridge data collection stage[49–53]. The large amount of collected data will be pre-processed, e.g. using edge devices, and the procedure includes several stages: data inspection, time window selection, digital filtering, exponential windowing, and time domain or frequency domain averaging[112]. The pre-processed data can be transmitted to a BIM CDE via 5G, optical fiber transceiver system, or high speed WIFI. CDE is a common digital project space that provides well-defined access areas for the project stakeholders combined with clear status definitions and a robust workflow description for sharing and approval processes[87].

5.3.2. *Data applications*

Molding is the primary data application in bridge engineering, including simulation models, surrogate models, 3D surface models, and information models.

Simulation is a commonly used and effective method in analyzing bridge structures. A bridge model is established based on a bridge's actual geometric dimensions and material properties through finite element software such as Ansys, Abaqus, and Midas. Then the bridge's structural response under earthquake, wind, vehicle loads, or other action is obtained through calculation[55,56]]. The simulation can also be applied to the subsidiary structure of a bridge. For example, with an earthquake, it is easy to cause damage to viaduct or railway bridge light poles or telegraph poles, affecting the lighting and pushing safety hazards[57].

The surrogate model relies on AI technologies, such as machine learning and deep learning, which can fully explore the relationship between data and are mainly used in the bridge maintenance stage[54–57,113].

3D surfaces model can use 2D picture to get objective bridge surface condition data, it can also use 3D scanning with point cloud processing for inverse modeling. In this process, drones and robots will gradually be used to replace manual bridge inspectors.

BIM can also be constructed using Knowledge graphs. Knowledge graphs, also known as semantic networks, which transform information generated throughout the life cycle of a bridge into computer-readable knowledge, are increasingly being used in bridges[58–60,69]. Yan and Hajjar [69] performed the automatic semantic segmentation of laser point clouds collected from steel girder bridges based on heuristic algorithms, thus facilitating the application of laser scanning in bridge inspection and management. Xia et al. [58]proposed a combined method based on local descriptors and machine learning to automatically detect the structural components of bridges from point clouds through automatic semantic segmentation. In addition, Semantic Web technologies such as ontology are characterized by the integration of multi-domain knowledge and can therefore be used for integrated decision making[61–64].

5.3.3. *Data visualization*

The high dimensional visualization of data will facilitate the human-computer interaction experience. The advent of virtual reality allows users to immerse themselves in a whole 3D experience and connect physical objects to the virtual world. For example, VR technology [117] has shown its increasing use as an effective visualization tool in civil engineering. Virtual Reality (VR) is defined as "a computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment"[65]. However, the existing literature on bridge monitoring using VR does not cover all bridge types and is mainly effective for reinforced concrete bridges[66–68]. For example, Omer et al. [67]applied a combination of LiDAR and VR for the first time to VR inspection technology for reinforced concrete bridges. LiDAR was used to capture a 3D image of the geometric surface of the bridge, including all defects. The images were post-processed, and a VR application was created using Unity (a software development kit) to inspect the bridge in an immersive 3D virtual environment.

Kilic and Caner [66] described the benefits of using AR technology in combination with visual inspections, ground-penetrating radar (GPR), laser distance sensors (LDS), infrared thermography (IRT), and telescopic camera (TC) applications. Using this method, potential weaknesses in the internal structure of a bridge, such as cracks and reinforcement corrosion, can be identified, thus improving the decision-making ability of structural engineers and asset managers.

Hu et al. [68]developed a framework to visualize the bridge deterioration detected and characterized through GPR scanning using AR technology. For this purpose, a vision and position-tracking-based AR system was designed to integrate with bridge decks GPR assessment. This framework could be integrated into a tablet, mobile phone, or mixed-reality headset. Field experiments were conducted. The method provided sufficient and timely information for preventive maintenance, thus extending the life of a bridge and reducing lifecycle costs.

5.4. *Concept Evolution*

BIM is defined as the "use of a shared digital representation of a built object (including buildings, bridges, roads) to facilitate design, construction, and operation processes to form a reliable basis for decisions."[114]. Similar to BIM, the definition of a DT is a digital representation of an actual physical object [115].

The focus of both definitions is not on the static representation of an object but rather on its dynamics over time during its life cycle. Despite BIM and DT technologies showing different development paths, there are some points of interactions in terms of the classification and function of the level of development due to both o them ultimately aiming to form a digital (virtual) simulation of a physical object from the real world and to create a link between natural and physical objects. Therefore, the conceptual layer is used to link BIM with the concept of DT. It shows the transition from BIM 2.0 to BIM 3.0, where DT is the main engine of this transition in the bridge engineering. Table 8 shows the 'BIM Levels' outlined by the UK Government's Building Information Modeling Industry Task G [116], including BIM Level 0, BIM Level 1, BIM Level 2, and BIM Level 3. The latest Government Construction Strategy, published in March 2016, seeks to embed BIM Level 2 across different departments, which will, in turn, "enable departments to move to BIM Level 3" [80]. BIM level 3 is divided into 4steps as shown below.

Level 3A Enabling improvements in the Level 2 model;
Level 3B Enabling new technologies and systems;
Level 3C Enabling the development of new business models;
Level 3D Capitalizing on world leadership.

From the strategy of BIM 3.0, it can be seen that each department intends to feed new advanced technology, and DT can align with this strategy very enable the life cycle and across departments BIM 3.0.

Table 8 Conceptual relationship between BIM and DT

BIM Level	Definition	Representative Technologies
BIM Level 0	-2D CAD drafting utilized - no collaboration.	2D CAD
BIM Level 1	-Mixture of 3D concept work and 2D for drafting statutory approval documentation. -Electronic sharing of data using a common data environment (CDE). -No collaboration between parties but data is shared	2D&3D
BIM Level 2	-All parties use their 3D CAD models, not necessarily working on a single, shared model.	3D BIM, 4D BIM, 5D BIM,

	-Collaboration is used. Data is exchanged between parties, and design information is shared in a single file format. -Federated BIM model is created. Each party can combine data with its own to make checks.	6D BIM
BIM Level 3	-Full collaboration between all disciplines using a single, shared project model held in a centralized repository.	Digital Twin

As shown in Figure 8, BIM 2.0 focuses on the design and construction phases, mainly for design modeling and construction management, considering time, cost, energy, etc. BIM 3.0 covers the concept of DT, which focuses on the operation phase by integrating multiple technologies to achieve eight significant steps, from data collection to human-machine interaction. Meanwhile, BIM 3.0 performs digital transformation and complete linkage management for the whole life cycle of the bridge based on BIM 2.0. Besides, the figure shows the mapping relationship from Pre-Bridge DT to Ideal-Bridge DT and BIM3.0A to BIM3.0B.

5.5. *Bridge DT Implementation Barriers*

Through the hierarchical definition and framework development of Bridge DT, it can be seen that the advanced progression from Pre-Bridge DT to Ideal-Bridge DT is mainly reflected in the following aspects: (1) advancement in acquiring and utilizing real-time bridge data; (2) advanced level of data flow automation; (3) advanced level of model integration and interaction; (4) advanced feedback capabilities

In order to realize the advanced development of the Bridge DT for the above aspects, some implementation barriers need to be addressed, and they are concluded as follows:

(1) Real-time performance. DT technology has significant requirements for real-time updates of twin models. Data transmission through smart sensors needs to synchronize between the natural world and computer systems in real time. Current DT can not achieve this feature yet, e.g. However, image data captured by drones and inspection robots still cannot be fully digitalized and automatically used for updating DT. It requires significant personnel and time to process image and updating models.

(2) Lack of a unified open-source platform for integrating and visualizing the various modules / datasets within the Bridge DT, as most current software solutions are limited to model creation/simulation instead of complete twinning.

(3) Lack of means of intuitive interaction with the internal Bridge DT model.

(4) The lack of AI based learning capability is another shortcoming for the current Bridge DT. The structural analysis of bridges using numerical simulation cannot simultaneously consider the multi and complex loads in the bridge environment (such as vehicle loads, wind loads, seismic loads, temperature loads, etc.). At the same time, the numerical analysis speed is often slow, and real-time analysis cannot be realized. Advance artificial intelligence are required to be developed to fully leverage the potential value of bridge data and improve the efficiency of DT data transmission.

(5) A large amount of existing aging bridges are still lack of monitoring data, or in isolated formats and can not be utilized reasonably. Therefore, it is necessary to supplement the missing or incomplete data of the bridge and determine the reasonableness of the additional value to ensure the accuracy of the DT analysis results.

6. Conclusion

This paper reviews 123 published documents regarding BIM and DT, presenting the latest technological advances and research trends on BIM and DT with a specific perspective on bridge engineering. It has been concluded that DT-enhanced BIM can help to bridge towards the full life cycle and across sector digital construction. The fusion of DT into the mature BIM framework can push BIM further upgrading from its 2.0 to 3.0 stage and reciprocally bring more unified and integrated applications of DT into bridge and wider construction engineering.

This paper comprehensively analyzes the existing DT definition and classification concepts, identifies DT functional KPIs, and hierarchically classifies the maturity and functional characteristics of DTs for bridge engineering. The ideal Bridge DT and its concrete form under the five-dimensional frame have been further concluded and presented, it can help to clarify the confusion of Bridge DT's definitions to fully explore the value of DTs in bridge engineering. A DT-enhanced BIM development framework for shaping full life cycle bridge engineering is proposed. The framework includes the life cycle process, the functional and implementation process, and conceptual evolution. The functional and implementation processes cover from the design of physical entities to the feedback of virtual entities and the life cycle data flow routes, along with typical implementation methods and tools. The conceptual layer shows the different levels of BIM and Bridge DT, which can facilitate the conceptual integration of BIM and Bridge DT throughout the whole bridge life cycle. This framework is expected to contribute actively to the future development of BIM and DT and their integrated advanced technologies.

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