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Towards Civil Engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure

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ABSTRACT

Digital Twins (DTs) are forecasted to be used in two-thirds of large industrial companies in the next decade. In the Architecture, Engineering and Construction (AEC) sector, their actual application is still largely at the prototype stage. Industry and academia are currently reconciling many competing definitions and unclear processes for developing DTs. There is a compelling need to establish DTs as practice in AEC by developing common procedures and standards tailored to the sector's procedures and use cases. This paper proposes a step-by-step workflow process for developing a DT for an existing asset in the built environment, providing a proof-of-concept case study based on the Clifton Suspension Bridge in Bristol (UK). To achieve its aim, this paper *(i)* reviews the state-of-the-art of DTs in Civil Engineering, *(ii)* proposes a working DT-based workflow framework for the built environment applicable to existing assets, *(iii)* applies the framework and develops of the physical-virtual architecture to a case study of bridge management, and finally (*iv*) discusses insights from the application. The main novelty lies in the development of a versatile methodological framework that can be applied to the broad context of civil infrastructure. This paper's importance resides in the knowledge challenge, value proposition and operation dictated by developing a DT workflow for the built environment, which ultimately represents a relevant use case for the digital transformation of national infrastructure.

1. Introduction

Advances in computational technology (e.g. digitalisation and data management) have led to a new era of revolutionary innovation, i.e. the so-called Industry 4.0. The concept of a Digital Twin (DT) is one of the uncontested protagonists of this change: the global DT market was valued at USD $3.8bn in 2019, and it is expected to rise to USD $35.8bn by 2025 [1]. The two-thirds of large industrial companies will be deploying at least one DT in the next decade, resulting in a 10% improvement in effectiveness [2]. In the Architecture, Engineering and Construction (AEC) sector, the actual application of DTs is still largely at the prototype stage, while there is a lack of established protocols and standards to develop a common narrative and guidance [3]. Industry and academia are currently reconciling many competing definitions and unclear processes for developing DTs, especially for existing (legacy) infrastructure which is much less likely to have a digital representation than newly-constructed ones [4].

This paper utilises the DT definition provided by the UK's National Digital Twin Programme, i.e. "a realistic digital representation of assets, processes and systems" with a defining characteristic of a data connection between the real world and its digital representation [5]. The synchronisation between the state of the real-world asset/process/system and its virtual (also called digital or computational) representation is the key feature that distinguishes the DT from any other digital representation model (e.g. BIM). The way this synchronisation is achieved, the frequency with which the virtual representation is updated and how the virtual representation is used can further characterise the DT. For example, a DT may form an active part of a cybernetic control system (like a thermostat) to directly control the behaviour of its tangible counterpart, or it may take a more passive role, e.g. informing decision-making processes in building maintenance. DTs exist at many scales and levels of complexity, from a single component (e.g. bridge saddle or car

Acronyms: AEC, Architecture, Engineering and Construction; AI, Artificial Intelligence; BIM, Building Information Modelling; CSB, Clifton Suspension Bridge; CSBT, Clifton Suspension Bridge Trust; DT, Digital Twin; FE, Finite Element; FEM, Finite Element Model; IoT, Internet of Things; SHM, Structural Health Monitoring; WSN, Wireless Sensor Network.

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seat) or asset (e.g. bridge or train car) to systems of connected DTs (e.g. a car's DT sending signals to a highway DT), up to an ecosystem of connected DTs (e.g. networks of service-based assets, such as healthcare facilities or transport) [6]. When all the urban ecosystems are connected, a National Digital Twin can be ultimately achieved. The first step for practically establishing DTs in AEC is to develop common standards (e.g. ISO Group on Industrial Data, ISO/DIS 23247-1) and processes tailored to the sector's practices and use cases. This paper aims to develop a generic step-by-step workflow process for developing a DT for existing assets, providing a proof-of-concept case study (the Clifton Suspension Bridge in Bristol, UK).

1.1. Motivation and aim

Civil Engineering, and more generally the AEC industry, is still significantly behind other industries in the use of DTs. In the built environment, DT application is just beginning to take off, since "fully realised examples are rare, even at the level of individual assets" [6] and "their form and formats are yet to be fully developed" [1]. DTs are seen as something very complex and difficult to achieve [1], whose "processes are uncertain and in their relative infancy" [7]. The first step for establishing DTs as practice in AEC is to develop common frameworks and processes. Current literature and practice lack practical insights into the "real-virtual-link" paradigm, e.g. how enquiring into the real structure should be performed and how the virtual structure should be designed and the link implemented. This paper aims to develop a step-by-step workflow process for developing a DT for an existing asset in the built environment, providing a proof-of-concept case study, based on the Clifton Suspension Bridge in Bristol (UK); the process is implemented on a specific asset which makes the concept more accessible to a range of stakeholders (industry, modellers, researchers, infrastructure managers), especially considering the majority of structures that do not have pre-existing BIM data. The aim is achieved through the following objectives*: (i)* reviewing the state-of-the-art of DT in Civil Engineering; *(ii)* proposing a working DT-based workflow framework for the built environment applicable to existing assets, aligned with the state-of-the-art guidance; *(iii)* applying the framework and developing the physical-virtual architecture for a case study of bridge management; (*iv*) discussing insights from the application and its potential of DT for future studies. The novelty of this paper is in illustrating a step-by-step methodology of twinning, which is not limited to a methodological framework but applies to civil infrastructure more broadly. This paper's importance resides in the knowledge challenge, value proposition and operation dictated by developing a DT workflow for the built environment, which ultimately represents a relevant use case for the digital transformation of the UK's infrastructure.

2. Background

Historically, the concept of replicating reality is not new. Engineers have always used models of the real world in the form of paper-based diagrams, calculations, physical scale or computer models. Models simplify the real elements by extracting the structure and processes they represent and "do not aim to replicate the original system" [8,9]. The origins of DTs are traced back to the 'mirrored images' and "physical twin" of Apollo 13 that NASA created in 1970 [10] to test possible solutions. The concept was then re-proposed in the Winter Simulation Conference 1992 (New York), where DTs were generally denoted as 'simulation models' to assist with problem-solving and decision making, although their validity was questionable [11]. The first use of the contemporary term "Digital Twin" came in 2002 when Grieves [12] defined a DT as a 'Conceptual Ideal for Product Lifecycle Management' [13,14]. In the last decade, DTs have been refined (e.g. [13,15]), and their application has flourished in the manufacturing industry, where they allowed faster production time, cost reduction, and prediction of system malfunctions [14,16]. The concept has also been successfully implemented for aircraft and NASA spaceships [17,18], Formula 1 vehicles [19], and offshore oil and gas facilities [20]. Detailed reviews are available in the literature regarding the evolution process of DTs (e.g. [21,22,14,23]).

Conceptually, DTs include three parts [5,22]: *(i)* the physical entity (the real-world object) set in the physical environment; *(ii)* the virtual entity (the virtual counterpart) set in the virtual environment; and *(iii)* the two-way "link", which is the Virtual-to-Physical and Physical-to-Virtual connection. A DT becomes useful when designed to relate with the user's "experience", e.g. specific goals and actions within infrastructure managers and/or operators (Fig. 1). The ability of "twinning" is the unique capacity of synchronising the virtual and physical states with a continuous cycle of updating; the "twinning rate" is the frequency at which twinning happens. In literature, the DT twinning rate is usually considered in real-time or near-real-time, i.e. a change in the physical state is near-instantly acknowledged by the virtual state [22].

The access to as-built and as-designed models, which are synchronised with data, makes DTs the appropriate technology that can help tackle a range of urban challenges, in particular in asset management [25]. DTs allows for grounding monitoring, management and improved life-cycle management on a data-driven and knowledge-based approach towards four streams of application [4]: *(i)* supply and demand, i.e. make the whole supply-chain more transparent and efficient; *(ii)* operations and performance, i.e. support monitoring and predictive maintenance, as well as early-warning and disaster preparedness; *(iii)* live data management, i.e. support the management of assets to optimise processes, planning, decision-making and budgeting; *(iv)* simulation purposes, i.e. test prototypes and scenarios, factoring in external parameters such as accidents or climate change. As a result, DTs are perceived to improve efficiency, security, safety, reliability, decision-making and flexibility, while reducing costs, risks and design time [22,23,26]. Ultimately, DTs foster innovation [22] and could help achieve the United Nations' Sustainable Development Goals [4].

Despite the clear potential of DTs, multiple barriers prevent their wide application. Firstly, there is a lack of tangible understanding of the potential benefits, and the value of a DT (e.g. business models) is yet to be defined. Secondly, DTs require a high level of expertise, interoperability of models and multiple stakeholders. A further challenge is the computing demand due to data collection, digitisation representation and real-time synchronisation, alongside the high dependence on IoT. Finally, data collection relates to issues of accuracy and storage, privacy and security, IP protection and data exchange [4,6]. Overall, it is difficult to develop a business case that justifies the investment (and the complexity), and the DT revolution seems to need a social and cultural change of the workflow [4].

The limited demonstration of DT's value starts from a gap in the practice centred on the low level of development ([4], see Section 2.1). Also, DTs in the built environment are underrepresented, and detailed

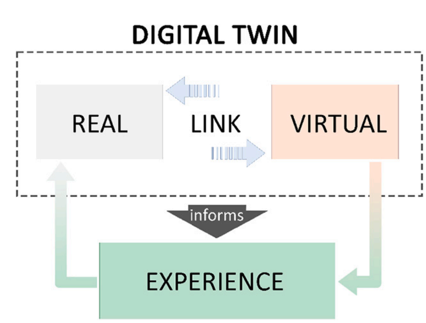

Fig. 1. Typical Digital Twin (DT) components: the real, the virtual and the link. The DT needs to relate to the real world "experience" in order to be "purposeful" [24], e.g. specific goals and actions within infrastructure managers and/or operators (considering the Architecture, Engineering and Construction sector).

studies are recommended to align sector competency to technical and managerial aspects while exploring the relationship among DTs, outcomes and principles [6]. Further advances in modelling and simulation are needed to establish DTs in AEC practice.

2.1. State-of-the-art in Civil Engineering

The Digital Twin (DT) literature has mainly emerged in the last 10 years, with 96% of related publications arising since 2016 [6] and most (~50%) related to manufacturing and production [22], with very little in the built environment (~5%). In the AEC sector, the conception and modelling capability of the DT begins with the BIM (Section 2.2) and continues with integrating sensing capabilities, big data and IoT. The application of such a combined data-driven, digital and modelling approach has very recently been extended to civil engineering assets (such as buildings, wind turbines and power plants) for improving monitoring, maintenance and performance of physical entities. The difficulty and lack of uptake of DTs in Civil Engineering (c.f. manufacturing, etc.) could also include the normal slow rate of change of the state of its assets, which does not fit very well with the original essence of live DTs. In fact, the shift from "real-time" to "right time" of twinning [27] seems to fit better cases where regular updates (as opposed to living ones) suffice.

In the last years, AEC has embraced the concept of DT, and various initiatives can be found to steer its development. In the UK, several bodies, from the government's National Infrastructure Commission (NIC) to the Institution of Engineering and Technology (IET), the Institution of Civil Engineers (ICE) and the Open Data Institute (ODI), are all staunch advocates of developing the potential reach of the technology. In particular, in 2018 the UK government has supported the development of a National Digital Twin programme led by the Centre for Digital Built Britain (CDBB). The National Infrastructure Commission (NIC) and the UK Government's Digital Framework Task Group followed with the Gemini Principles [24,6,28], which set the foundations for DTs in Civil Engineering [4,1,26]. The three Gemini Principles are [24]*: (i)* a DT must be purposeful, in terms of public good, value creation or insight; *(ii)* a DT must be trustworthy, in terms of security, openness and quality; *(iii)* a DT must be functional, in terms of federation (i.e. based on standards), curation (i.e. clear ownership and regulation) and evolution. However, these principles remain quite generic since they do not go down to specific technological solutions [6]. Overall, the large strategic discussion on DTs has been limitedly associated with practice so far.

CDBB works in strict collaboration with industry and institutions (e.g. Bentley systems, Cambridge University Institute for Manufacturing (IfM), ICE's digital transformation group, BSI). Key civil engineering consultancies (e.g. Arup, Mott MacDonald) have aligned their agenda with the DT vision as well, and pioneered reports about their potential application [4,1,29]. Arup [4] presents four metrics (autonomy, intelligence, learning, and fidelity) to evaluate from 1 to 5 the current state of DTs. Level 1 is when the virtual-real connection is present, however, the twinning has limited functionality, e.g. a basic model or a map; Level 2 is when there is some capacity for feedback and control, however, the DT is limited to small-scale systems, e.g. house temperature sensors which inform a human operator; Level 3 is when the DT allows for predictive maintenance and analytics, e.g. early-warning system of failure for rail infrastructure; Level 4 is when a DT is able to learn about the surrounding environment through various data sources and has autonomous decision-making for a specific task. e.g. real-time route recommendations for drivers; Level 5 is when the DT ultimately approaches the ability of autonomous reasoning and acting on behalf of the users using AI, with the capacity to react to unpredicted scenarios and interconnect with other systems (or DTs), e.g. multiple infrastructure networks providing feedback to a city-level decision-making hub. Among the nine case studies presented in the report, none were up to Level 4 or 5, one was judged at Level 3 only, proving the need for further applied studies.

Despite these futuristic agendas, the actual application and technology is still at the prototype stage. The first stepping stone to enable this vision is identified in the creation of DTs for individual assets [26], which work as "an optimised system" [30]. For example, DT-supported monitoring and maintenance could prevent catastrophic episodes by tackling chronic stresses (ageing infrastructure) and unexpected events/acute shocks. In fact, the failure of the Tadcaster Bridge (2015) is chosen as an example of DT application for increasing flood resilience [5]. The integration of SHM (structural health monitoring) data, BIM, FE (Finite Element) and statistical modelling seems the next direction of research to improve monitoring and the whole-life management of structures (e.g. bridges, [31]). Ye et al. [31] suggested the key benefits of DT for a bridge include efficient data queries, integrated data processing capabilities and a single collaborative environment throughout the lifecycle, but concluded further work is required for integrating data and models. From a practical point of view, the implementation of a DT remains a challenge: the level of complexity is high, and a unified process has not yet been defined.

There are few papers that focus on the core concept of DTs in Civil Engineering [22]. Dang et al. [32] suggested a 3D DT model for typical bridge structures for the next generation of bridge maintenance systems. This consists of a very high-level framework for the interoperability of 3D, FE and damage models. Their twin model concept lies on the integration of two models: *(i)* a 3D model which includes material properties and damage/deterioration records; and *(ii)* a FE analysis model which considers the change of structural parameters (e.g. cracks, material degradation, corrosion of steel elements). Environmental conditions, including temperature, humidity, loading history, and monitoring data, are essential information for future performance prediction. The method was not applied. Similarly, Ye et al. [31] offered an overview of the necessary capabilities required for a DT of two railway bridges to perform early-age behaviour assessment for structural health monitoring purposes. Also Shim et al. [33] presented a DT-based model concept for bridge maintenance and more reliable decision-making. This study was a theoretical approach to DT modelling and not detailed in its steps or with a case study. This work progressed into Shim et al. [34], who offered a DT model for a suspension bridge and for stiffening girder, applied to a pilot for maintenance and automatic damage in Korea. Sensor data from the monitoring system was embedded and led to the field-verified structural behaviour of the FE analysis model. However, the flowchart model was not detailed and did not set a transferable DT framework. Lu and Brilakis [35] illustrated the automation of digital twinning for existing reinforced concrete bridges, using cloud-to-cloud distance-based metrics. Their work aimed at fitting a 3D solid model to labelled point clusters and was not focused on the twinning concept. However, it reported a real case application, specifically to ten highway bridges around Cambridgeshire (UK). In the same geographical area, Lu et al. [36,37] developed a DT-enabled anomaly detection system for built asset monitoring in operation and maintenance. They developed a process flow and a pilot for circulating pumps in a building's HVAC system, which was further extended by Lu et al. [38]. Their study presented a system architecture intended at both building- and city-level; the infrastructure level (or infrastructure assets) was not explicitly considered. The architecture comprises five layers: data acquisition, transmission, digital modelling, data/integration and service. This DT was used for condition monitoring and future performance prediction; however, the demonstrator did not practically include data synchronisation. Others have investigated the incorporation of real-time sensor data into BIM-like bridge models [39,40].

In the wider Civil Engineering sector, examples of ongoing DT applications and ambitions at asset-level include: *(i)* energy performance and carbon emission reduction [41,42]; *(ii)* the management of drinking water distribution networks [43]; *(iii)* sustainability assessment (e.g. of railway station buildings, [44]); (iv) a ground resistance model for liquefaction risk assessment [45]. These studies are not focused on developing transferable procedures. DTs at the city-level (e.g. [46]) or national DTs are out of the scope of this review and study.

2.2. BIM and DT

In the last decades, BIM (Building Information Modelling) has provided a framework to enrich data handling throughout the lifecycle of built environment assets. This capability progresses through a number of maturity levels from a standardised, but otherwise fragmented, common data environment (BIM Level 1) to a collaborative data exchange that integrates different data models (BIM Level 2) and finally to a fully open integrated network of data models (BIM Level 3). BIM has also evolved through a number of dimensions. 3D BIM refers to the shared integrated data model, which forms the baseline of Level 2. 3D BIM, in this sense, covers a range of information models (e.g. material properties, asset data etc.) and is not limited to three-dimensional graphical renders. Higher dimensions of BIM concern the construction schedule (4D), costs (5D) and lifecycle data for management of operations (6D). As opposed to traditional virtual models used for simulation, BIM systems are comprehensive parametric (most commonly 3D) models within a Common Data Environment which includes all the elements and features necessary for both design and construction. These elements are defined by parameters in terms of geometry, materials and performance, which are interconnected (e.g. adding an extra component would automatically increase the cost of construction). BIM has benefitted the construction sector by reducing errors and omissions (by 61%), constructions costs (by 20–30%) and project duration (by 20%) [41].

BIM and DTs have similar definitions; however, they differ in multiple ways [47]: *(i)* digital environment: BIM focuses on the building, not the interactions of the building with external factors, while DTs relate to both the physical (data) and virtual (models) environments; *(ii)* time: BIM offers static models, while DTs track changes to assets over time and update the models accordingly, enabling those responsible for asset management to roll the virtual representation of the infrastructure asset and related real-world conditions forward or backward in time. BIM and DTs are essentially both problem-solvers, but of different questions and objectives: BIM has been traditionally concerned with the management of consistent, traceable data that follows common structures, definitions and logic at the front end of projects (i.e. planning, design and construction); even 6D BIM which seeks to include data for whole lifecycle facilities management is not tuned for real-time operational response, interoperability and automation since it does not link live data during the life-cycle of the asset or use live calculation models. However, BIM's use of data models presents opportunities for their development into DTs within AEC at both asset- and city-scale [21,48]. This development is challenged by: *(i)* the fact that BIM is still an emerging technology itself (40% of contemporary new-build projects; [49]); and *(ii)* the even lower incidence of the retrospective application of BIM to existing assets (also known as 'Historic BIM'). A report by Historic England into the retrospective application of BIM [50] suggested it is "very unlikely" that any existing assets would have data electronically that would meet the standard for BIM during the operational phase of a built asset lifecycle (PAS 1192-3, now ISO 19650-3:2020). In other words, most legacy infrastructure will not have pre-existing BIM data models and therefore require different DT workflows to the newer infrastructure assets which do (i.e. those that are evolving their BIM into a DT). Furthermore, the collection and maintenance of BIM data, when applied to existing assets, can present many challenges [51] and, as a result, has been found to be complex and costly [52].

3. Workflow

The proposed workflow framework builds on the DT maturity spectrum presented in Evans et al. [1] and the five layers of [38]; see Section 2.1). A framework of five actionable steps is advanced (architectural diagram of Fig. 2 and detailed process in Fig. 3) and integrated with the relevant Gemini Principles (GPs) [24,6]. The steps are outlined below and shown diagrammatically in Table 1.

(1) *Data and need acquisition.* This step consists of an enquiry into the 'real' structure, that elicits the persistent information required for model building. This step generates information into the operational processes used to manage a structure, clearly identifying the objectives and decisions that the DT will support, as well as the actions that provide the feedback between the DT and structure. GPs: *Purpose, Insight, Value creation.*
(2) *Digital modelling.* This step involves the creation of a 'virtual' model that simulates, visualises, controls, models the behaviour of the structure. Depending on the purpose of the DT, multiple

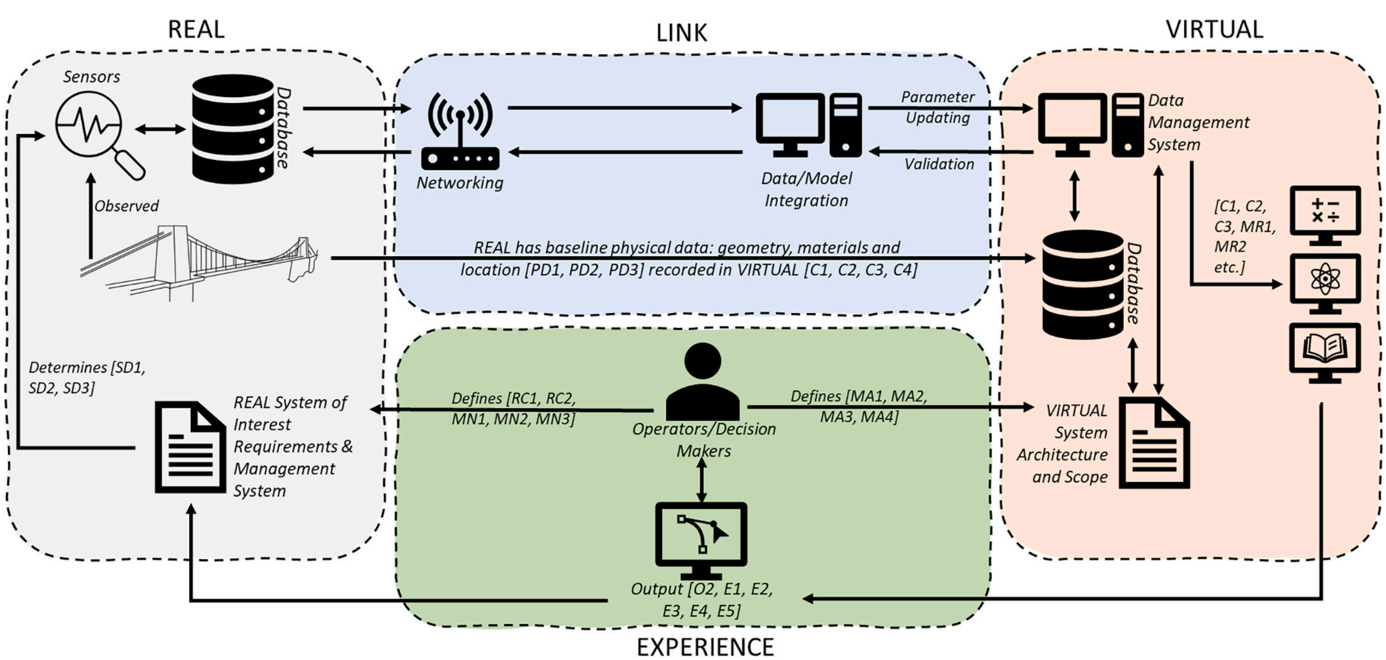

Fig. 2. Architectural diagram. PD "Physical Data"; MN "Management Needs"; SD "Sensor Data"; RC "Requirements Capture"; L "Link"; O; "Operation"; MR "Modelled Response"; C "Configuration"; MA "Modelled Architecture.

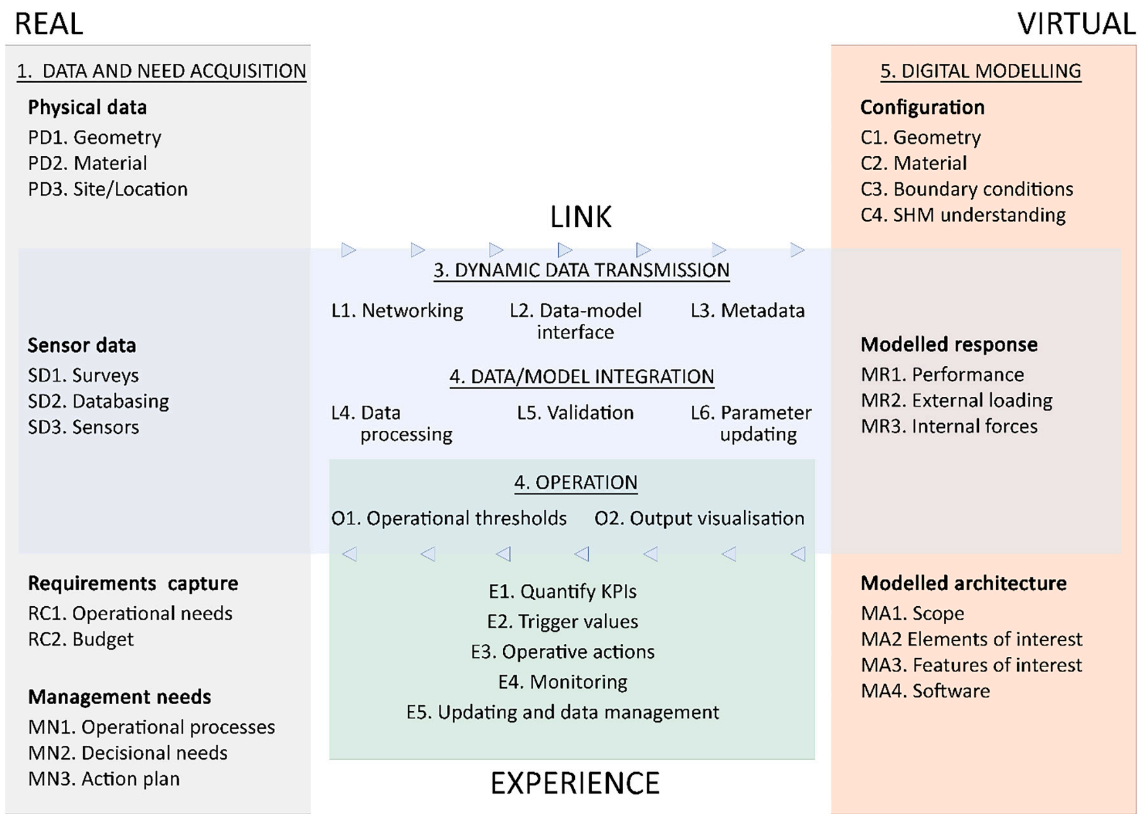

Fig. 3. Diagram of the component parts of any Digital Twin.

Table 1
The proposed five-step workflow to develop Digital Twins (*also part of Link).

		REAL								R&L			LINK						L&E		EXPERIENCE					V&L			VIRTUAL							
	STEP	PD1. Geometry	PD2. Material	PD3. Site/location	RC1. Operational needs	RC2. Budget	MN1. Operational processes	MN2. Decisional needs	MN3. Action plan	SD1. Surveys*	SD2. Databasing*	SD3. Sensors*	L1. Networking	L2. Data-model interface	L3. Metadata	L4. Data processing	L5. Validation	L6. Parameter updating	O1. Operational threshold	O2. Output visualisation	E1. Quantify KPIs	E2. Trigger values	E3. Operative actions	E4. Monitoring	E5. Updating & data	MR1. Performance*	MR2. External loading*	MR3. Internal Forces*	C1. Geometry	C2. Material	C3. Boundary conditions	C4. SHM understanding	MA1. Scope	MA2. Elements of interest	MA3. Features of interest	MA4. Software
1	1.01 Understand operational processes	•	•	•			•	•	•																											
	1.02 Understand operational requirements				•	•																														
	1.03 Identify data gaps									•	•	•																								
2	2.01 Define model scope																																•	•	•	
	2.02 Select model platform(s)																																			•
	2.03 Define model configuration																									•	•	•	•	•	•	•				
3	3.01 Define data interfaces													•																						
	3.02 Define metadata requirements														•																					
	3.02 Define data transmission												•																							
4	4.01 Identify data processing requirements															•																				
	4.02 Specify data revision rates																•																			
	4.03 Define validation requirements & methods																	•																		
5	5.01 Identify operational thresholds																		•		•	•	•	•	•											
	5.02 Define output formats																			•																

PD “Physical Data”; MN “Management Needs”; SD “Sensor Data”; RC “Requirements Capture”; L “Link”; O; “Operation”; MR “Modelled Response”; C “Configuration”; MA “Modelled Architecture” (see also Fig. 3).

compatible models may be required. Open and well-documented interfaces must be created if the model is to become part of a federated ecosystem of connected DTs, and these should be considered during the design stage. The DT must be able to combine models and data (e.g. for calibration, validation, updating, etc.), requiring suitable model interfaces. *GP: Openness, Federation.*

(3) *Sensor data transmission.* The collection of sensor data is the other element of the 'real' component of a DT. Suitable sensors (or observations) enable model validation and updating, while the data management elements facilitate automatic retrieval and processing. The sensing and transmission system must collect, transfer and store data, presenting it and its metadata through open interfaces for use by the integration framework. The necessary data quality (e.g. resolution and sample rate) depends on the requirements of the application and have an impact on the sensing and communications technology that can be used. The adoption of industry standards, both in technology and process, is also strongly advised as this will reduce design time and improve functionality. *GPs: Quality, Security, Federation.*

(4) *Data/model integration*. A DT peculiarity is the link between the real and virtual. An interoperability architecture guarantees this connection, which should be flexible and agile (through open platforms and a modular design) to accommodate advances in technology and society. At a systems-of-systems level (where outputs from one DT become inputs to another), a scalable federation requires the adoption of yet-to-be-created standards, as well as governance frameworks that clarify issues of data ownership and service level agreements. GPs: *Federation, Curation and evolution.*

(5) *Operation.* To inform and enable effective and efficient asset management actions should drive the purpose of a DT. A DT informs operational decisions when its outputs flow into the decision-making process, i.e. essentially about choosing which option for action is the best upon available information. Over time this will enable greater autonomy of operation and performance improvement. GPs: *Value creation, Public good, Insight, Security, Quality*.

The five actionable steps provide a process to create the DT components in a harmonised, joined-up way, as shown in the diagram of Fig. 3. The steps themselves are further described in the remainder of this section; the framework is applied to the case study of the Clifton Suspension Bridge in Section 4.

3.1. Data and need acquisition

A detailed enquiry into data and needs and focuses on understanding which problems need support (MN1 and MN2), what actions can be taken by the management of the structure and what decisions sit behind those actions (MN3).

A detailed enquiry into needs and resource is the first step, which focuses on understanding which problems need support, what actions can be taken by the management of the structure and what decisions sit behind those actions. This step provides the opportunity for enquiry into the 'real' and eliciting the persistent (or static, e.g. [53]) information needed to create the model. Information includes knowledge of the 'hard' structure data, i.e. physical data (geometry (PD1), materials (PD2), site properties (PD3)) and of the 'soft' processes and relationships. For many structures, 'hard' data exists in drawings, specifications, surveys, photographs and models originally used in design and construction; surveys (SD1) into existing data (e.g. from SHM systems) simplify the effort and cost of the DT. Sensor data (SD3) could derive from existing monitoring systems, e.g. toll barrier or weighbridge recordings [54]. In the case of new sensors, surveys include investigation about sensor type, location and transmission system.

'Soft' data includes management requirements, i.e. operational needs (RC1; accuracy, acceptable uncertainty) and available budget (RC2). Considering both aspects guarantee the DT *utility*, addressing the Gemini Principles of *insight* and *value creation*. As well as the content of any existing dataset, surveys investigate the process through which data are collected and would be acquired, to anticipate databasing (SD2) issues (e.g. data formats, ownership). These operational datasets have to be compatible with any new monitoring to be installed, as required.

3.2. Digital modelling

A mathematical model, implemented in software, is the virtual part of the DT, and aims at describing the structure and its state, managing data, providing functions, testing and forecasting scenarios. Modelling structures is well-covered in the literature [55], and widely used in industry. Therefore, this paper limits discussion to specific considerations relevant to DTs, namely: *(i)* the development of a model which links to a sensor network (and by extension the 'real' structure); and *(ii)* the timely operation of the model to return the required information. Also, this section provides the process of how a DT should be set up, rather than a description of current practice of virtual models.

The model architecture includes the wider model scope (MA1; e.g. what is the purpose of the model?) and the software platform (MA4). The model scope is aligned with the decision-making needs and identifies the elements (MA2) and features (MA3; e.g. loads which may come from codes and standards) of interest and for which modelling is required to define the effect of the loads on the structure. Usually, the goal is to appraise the status of those features of a structure that cannot be directly measured, and yet on which operational decisions are made. These features of interest may be specific to a single element of the structure (e.g. structural elements), or may be more emergent through the interactions of many elements (for example, a structure's natural frequencies). In this context, the capability of integration into a wider software architecture (compatible with the 'link' network) drives the choice among the range of available modelling packages (e.g. geotechnical software, various building services software); this requirement mandates that the package has a set of open, well-documented APIs (Application Programming Interfaces) allowing other pieces of software to modify the model parameters, invoke the operation of the simulation, and retrieve the modelled responses that are generated. This compatibility requirement is needed to guarantee the model synchronisation while also adhering to the *openness* principle.

The model's "inputs" are fundamental information of configuration such as geometry (C1), material (C2) and boundary (initial) conditions (C3). Supposing a full understanding of the SHM system (type, location of sensors, sensor data), the model configuration allows for data transmission and data/model integration, e.g. simplifying any conversion requirements for existing datasets. The model's output consists of the structure's response and, in particular, performance (MR1), which includes computing internal (MR2) and external (MR3) loading for any modelled state. The complexity of the model, and software packages running it, will govern the range of loadings that can be accurately simulated. A process of validation (L5; see Section 3.4) verifies if modelled features show a good fit with real-world measurement for a range of scenarios; this process is likely to be an iterative loop of error optimisation, especially when fundamental properties (e.g. Young's modulus) are estimates.

3.3. Dynamic data transmission

SHM [56] and its growing use of Wireless Sensor Networks (WSNs) [57] is well-covered in the literature, so this study focuses on the DT-specific issues of data handling and integration. The selection of sensor and data handling technology is based on the automatic retrieval and processing of data, as enabled (for example) by modern WSNs and open-source software platforms [54]. When integrating existing datasets, data is automatically synchronised and received. Clear and detailed documentation of such processes is crucial, as well as data transfer agreement to cover all parties' rights and privacy, adhering to the GPs of data *Quality*, *Security* and *Federation*.

Assuming the FE model and SHM system are both suitable for data/model integration, linking software will need to leverage the interfaces of both systems. Interfaces (L2) must allow the linking software to access the database for specific and relevant slices of the data (e.g. from a specific time range), to avoid unnecessary processing burden. The recording of metadata (L3; e.g. sensor calibration, model accuracy) is also important, and values should be retrievable based on the specific sensor they came from. Also, a SHM system will often record measurements to a database (for example, the time-series database InfluxDB; [54]). It is likely that processing will take place on sections of this historical record, as well as the live sensor readings.

Data is transmitted from where the sensors are deployed to a physical server capable of performing the necessary computation, for which networking (L1) is required. The range of networking options are extremely broad and dependant on the sensor deployment location, amount of sensor data that must be transmitted, the acceptable latency of the transmission and the operational cost budgeted for the system. Different sensors might rely on different physical networks to transmit their data, and this heterogeneity is acceptable as long as the different sensor data streams are unified and synchronise once they arrive at their destination. End-to-end encryption should be implemented to ensure that data cannot be intercepted, especially for sensitive data. Considering outputs underpin potentially safety-critical decisions, the network must also prevent the alteration or fabrication of sensor readings by using, for example, immutable logs for each record.

3.4. Data/model integration

One reason behind the *value creation* of the DT concept is the integrated framework that makes data exchange and processing, parameter updating and validation a smooth iterative loop [27]; however, to implement the real-virtual 'link' is non-trivial.

Not all measured data is used for validation, and some may have a more direct impact on model parameters, for example, deriving loadings from operational data. Some data processing (L4) of the recorded measurements may be required before they can be updated into the model, such as in the case of vehicle axle weights recorded by a weigh-in-motion machine. These measurements need to be converted into point loads, possibly taking into account estimated vehicle speed, before the model loadings can be modified accordingly. This conversion is achieved by linking the DT functionality with a processing engine able to perform the conversion. Processing is also required for model validation and updating: processed data need to be compatible with both the real sensor data and the model output/parameters. In fact, this step is underpinned by the GPs of *federation*, *curation* and *evolution*.

Parameter updating (L6) includes "tuning" the model to increase the fidelity of the model, making it a better representation of the real structure. The updating process depends on the number of parameters, data size and ultimate aim of the DT. A simple optimisation approach could be suitable for a small number of parameters, while data assimilation is better for larger numbers [27]. Data assimilation methods consist of approximating initial conditions and updating them as data become available to obtain more refined predictions (e.g. widely applied in meteorology). Assumptions are tested by running the model and comparing its response with the recorded response of the real structure. 'Manual tuning' techniques can be applied [58], where an engineer repeatedly reruns the model, targeting the parameters with the greatest uncertainty. By contrast, an operational DT continually performs this tuning process based on the SHM data it receives. Challenges arise from the very large number of adjustable parameters that can exist in a structural model, which can result in there being many different sets of parameter values that may match the measured structural response. Allowing a DT to automatically target the uncertainty in a model, and so select the parameter values that best represent the real structure, is an outstanding challenge. The computational expense associated with large data and/or the purpose of the DT means that instantaneous output and real-time updating is not useful or possible; whether this delay in the output is acceptable will depend on the DT requirements and scope.

A crucial difference between a traditional model and a DT is that at least some of the parameters of a DT model are expected to evolve over time, mimicking the changes (e.g. ageing) of the real structure. Changes in these 'target' parameters are likely to be of interest to infrastructure managers (especially if not independently verifiable), as they may infer meaning about the expected life of the structure. The linking software must be aware of the target parameters and track their change over time to give an insight into how the structure is ageing. Parameters that are not expected to change should be treated differently by the linking software. Here, as data is gathered over time, model validation (L5) is necessary to verify modelled values with recorded data, reduce uncertainty and increase the confidence of the DT outputs.

3.5. Operation

A critical aspect of infrastructure management comprises the identification of operation thresholds (O1), i.e. set of conditions at which an asset experiences a non-desired condition. The identification of operational thresholds is the integrated result of a complex process that encompasses the quantification of Key Performance Indicators (KPIs, e.g. stress, strains) and the identification of trigger values (E2; e.g. the level of earthquake/wind intensity), to which will correspond determined actions (E3; e.g. evacuate the building). The outcome of these actions is monitored (E4), in the light of initial thresholds, KPI and trigger values within an iterative process. Each decision that is made (either to act or not to act) is recorded alongside the sensor data and the virtual model parameters (E5) at that time in order to contribute to the broader iterative loop of updating, tuning and validating the DT (see Section 3.4). Data and sensor details and metadata (e.g. precision, sensitivity) are considered at this stage, especially in their relationship with the model and users/parties. Documented agreement(s) and digital format(s) underpin the secure transmission and unambiguous interpretation of measurement-related data (e.g. digital calibration certificates). This regulation sustains the GPs of *Security* and *Quality*. Thresholds, triggers and related actions (including unsatisfying outcomes) also feed into the eliciting mechanism, informing r*equirements capture* and *Management needs* (see Section 3.1). The operativity of a DT is within the GPs of *Insight* in the built environment, *Value Creation* with performance improvement and *Public Good*.

The actions and the overall operation monitoring are based on timely and relevant output values, which visualisation (O2) varies upon data type and the overall operational process. One option for routinely consultations is to use dashboards, i.e. a control panel with a graphical user interface functions for providing at-a-glance views of KPIs; periodic (daily, weekly, monthly) reports are an alternative option. Alerts and/or email/text notifications can also be set up when the identified thresholds are reached, especially for outputs triggering immediate actions.

4. Case study

The Grade I listed Clifton Suspension Bridge (CSB; Fig. 4) in Bristol (UK) spans the River Avon and was completed in 1864, based on a design by I. K. Brunel. It constitutes an excellent example of legacy infrastructure, with obvious ageing and maintenance issues [59,60] and no BIM data. Nonetheless, the bridge has been the subject of academic research, meaning some prior models exist of the structure for calibration and validation of the virtual model. The Clifton Suspension Bridge Trust (CSBT) is responsible for managing and maintaining the bridge; one of their concerns is the operation of the tower saddles, which may

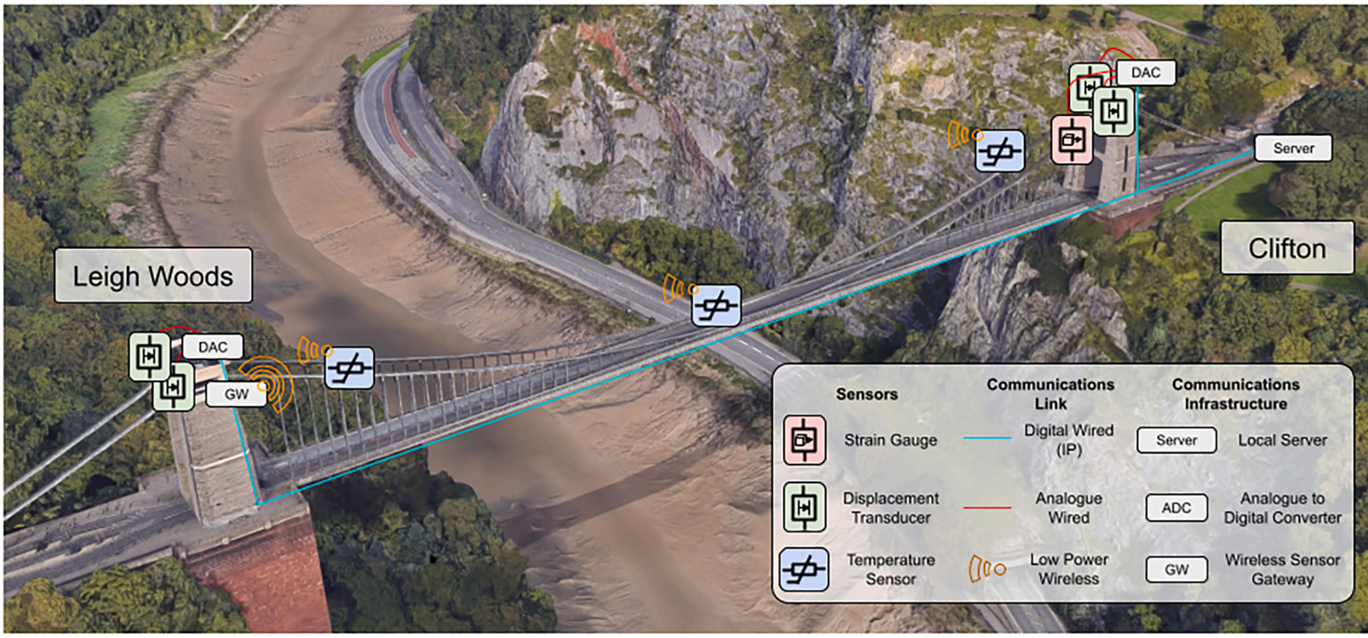

Fig. 4. The Clifton Suspension Bridge in Bristol (UK). An illustration of the sensor deployment required by the proposed saddle monitoring DT application (base photograph from Google Earth).

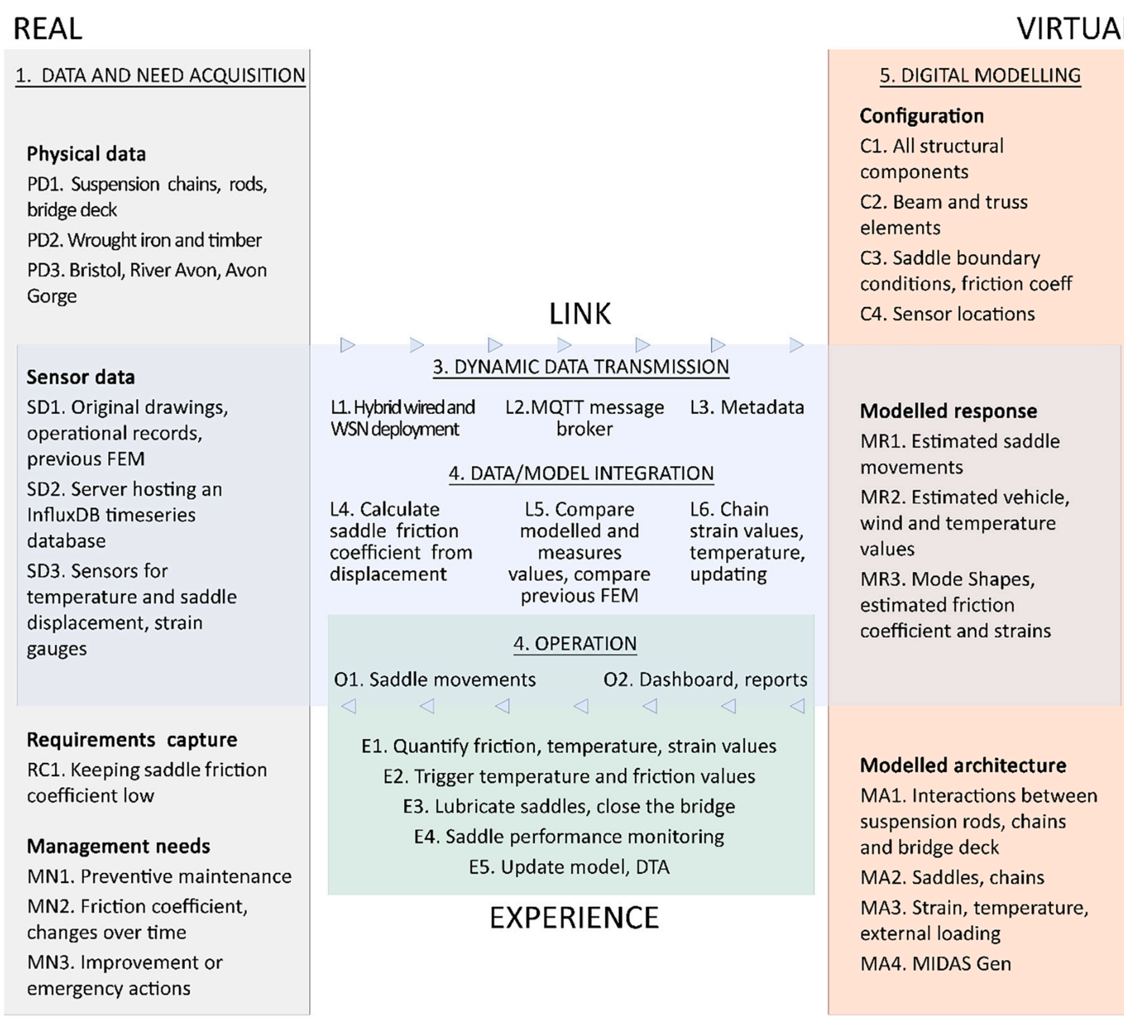

Fig. 5. The flow diagram updates the generic methodological framework and shows real actions, elements and systems for each step - in relation to the Clifton Suspension Bridge case study.

impair the bridge's safety. Currently, information about the saddles is presented to the bridgemaster in the form of a periodic report, whereas a system able to detect changes in the friction would allow managers to better quantify risk factors. This demonstration focuses on this operational need.

This study applies and demonstrates the workflow developed in Section 3 by tailoring each step onto actual actions, elements and system, as shown by Fig. 5; for the CSB, the capability of a DT is then illustrated for the specific case study, i.e. the monitoring of the tower saddles [75].

4.1. Data and need acquisition

Without BIM data to rely on, enquiry into the current state has included examining historical drawings and operational records from archives and site visits to inspect specific details in person (SO1). For this study, the CSBT and the bridge consultant COWI facilitated data, need acquisition and the model validation (Step 4, L5).

The key structural components are made of wrought iron. The main span, between centrelines of the piers, is 214 m, with chain side spans each of 60 m (Fig. 6a). The roadway is 6.1 m wide between the two longitudinal stiffening girders supported by vertical suspension rods at approximately 2.44 m spacing along the bridge deck. On either side of the deck, outside the girders, footways give a total deck width of 9.46 m between the centrelines of parapets (Fig. 6b). The deck is comparatively light, made of timber with wrought iron lattice cross-girders in line with each pair of suspension rods (PD1, PD2 and PD3; [61]).

The suspension chains supporting the bridge on each side of the roadway are formed as a system of three wrought iron sub-chains arranged, one above the other (as shown in Fig. 7a). These sub-chains are made of wrought iron bars with special eye joints forged to their ends. Each link of each chain is formed of 10, 11 or 12 bars arranged side by side, interleaved with the bars of the next link, and connected with a pin through the eye joint. Suspension rods (Fig. 7b) are attached successively every 2.44 m to each of the three chains in turn [63].

The main span chains and the anchor chains are connected at the top of the towers through a system of vertical iron plates bolted between a pair of iron castings sitting on a cast iron plate sitting on rollers that run on another iron plate, as shown in Fig. 7c. The anchor chains are supported through land saddles that guide the chains through a 25 m shaft inclined at approximately 45° to reinforced anchorages. The tower rollers minimise horizontal forces on the towers from the chains due to changes in loads and temperature, but this is only possible while the rollers move freely. If they seized, large forces could be transferred to the towers, which could significantly increase the stresses in the rock abutment. This abutment is a natural structure, so exact operational stress thresholds are not easy to identify. There is, therefore, an operational imperative to ensure that the frictional coefficient of the saddles is kept low (RC1). Understanding the change in the friction coefficient over time (MN2) allows bridge management to schedule preventive maintenance (MN1) and actions (MN3), e.g. lubricant application, or even bridge closure.

The expansion and contraction of the chains due to changes in temperature were identified by bridge consultant COWI as the cause of the largest impact on the force applied to the saddles [64]; thus, the bridge was instrumented with appropriate sensors (SO3; Fig. 4). Temperature sensors measure the temperature of chain links while displacement transducers (located on each saddle, two in each tower) measure the saddle displacements. The bridge tower on the East side has one strain gauge fitted to the chain links to measure strain on chain links at one saddle (see Section 4.3). Finally, two weather stations and two weigh-in-motion machines for measuring vehicles' weight are also in place.

4.2. Digital modelling

A 3D FEM (Finite Element Model) of the bridge has been developed by the authors to numerically simulate the response of the structure under loading conditions of interest. The software Midas Gen [65] (MA4) was selected for initial FE modelling. The geometry and cross-sectional properties of the bridge and its components are based on the NODLE FEM model developed by COWI [66]. The Midas GEN model has two main advancements with respect to previous models: *(i)* it includes the interlocking of the suspension rods with the lower two suspension chains; and *(ii)* the boundary conditions modelling the tower saddles have been modified to represent the actual behaviour better.

The whole structure of the CSB has been included in the 3D FEM (C1), excluding the towers that have been considered rigid. The deck cross-sections are user-defined to represent the geometrical properties of the wrought iron components. A timber deck is not providing significant

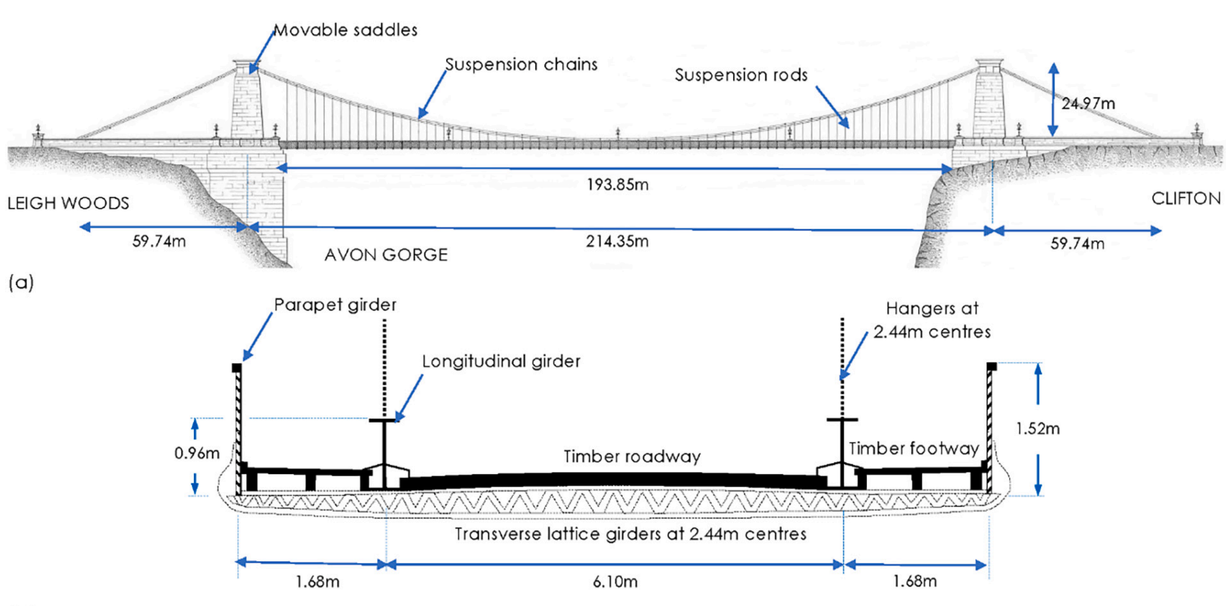

Fig. 6. Deck details of the Clifton Suspension Bridge: (a) South elevation (adapted from [61] - copyright © ICE Publishing, used with permission under the STM Permissions Guidelines); (b) cross section (modified after [62]).

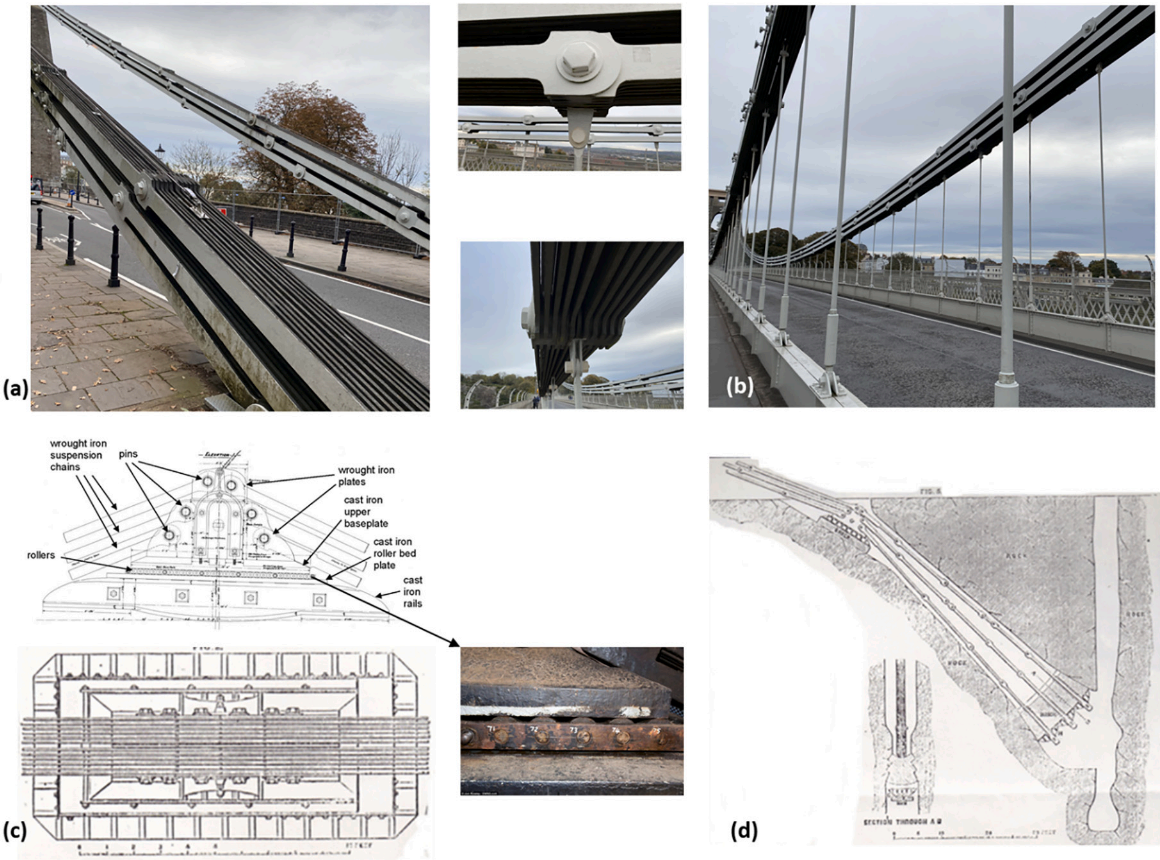

Fig. 7. Details of the suspension system of the Clifton Suspension Bridge: (a) suspension chains; (b) suspension rods; (c) rolling tower saddles (reproduced with permission; Copyright © Clifton Suspension Bridge Trust, see also archives.cliftonbridge.org.uk); (d) land saddles and anchors (reproduced with permission; Copyright © Clifton Suspension Bridge Trust, see also archives.cliftonbridge.org.uk).

stiffness and has not been modelled; its weight contribution has been included as dead load. The three separate chain elevations have been retained. The interchanging 10–11-12 chain links in the lateral sense are represented using appropriate user-defined cross-sections. Suspension chains and deck wrought iron cross-sections are modelled as beam elements since experimental end deflections, and natural frequencies were matched more accurately by modelling the bridge chains as beam elements instead of pin-ended bars [66]. The suspension rods are modelled as truss elements and are connected to the deck and chains using very stiff, weightless beam elements (C2). The interlocking of the suspension rods with the chain links has been considered using links as necessary. The idealised boundary conditions at land saddles (C3), tower saddles and deck, are shown in Fig. 8.

The model has been calibrated and validated against two previous numerical models (L5): *(i)* the NODLE model [66]; and *(ii)* a 3D FEM model developed in ANSYS [63]. Comparisons against experimental results of some selected symmetric load cases presented by Flint and Pugsley [67] generally show reasonable agreement. Modal analysis

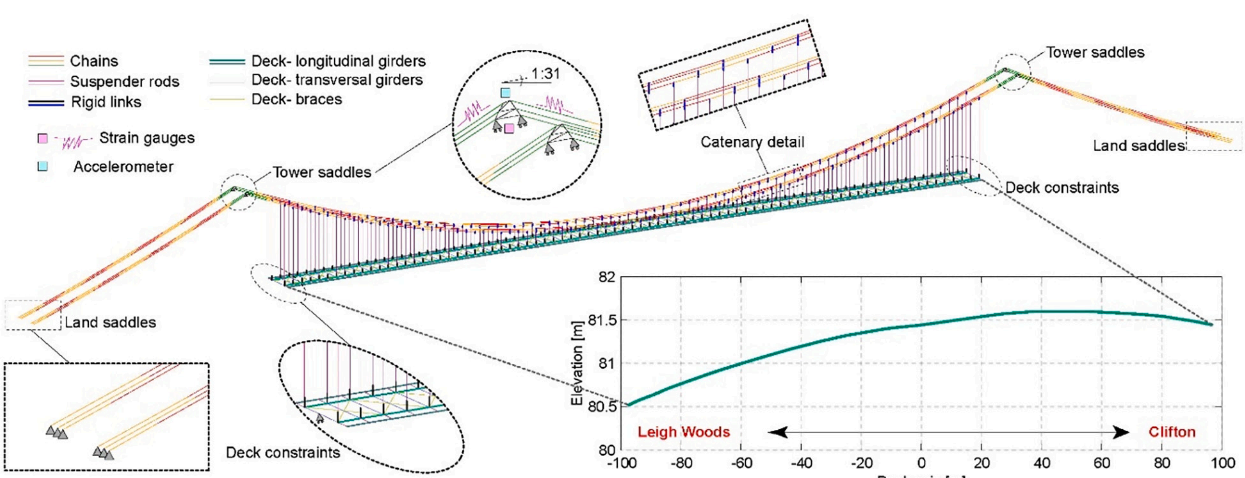

Fig. 8. CSB 3D FEM developed by the authors using Midas Gen platform and idealised boundary conditions assumed.

results show good agreement when comparing the vibration modes (Fig. 9a) to available experimental data [68,69] using the Modal Assurance Criterion (MAC) ([70]; mean MAC = 0.973). Fig. 9b shows the good fit between experimental (green) and numerical (red) vertical modes shapes.

4.3. Dynamic data transmission

As explained in Section 4.1, most of the deployment is limited to the tower tops, where wired communications (L1) are provisioned. Regarding the strain gauges fitted to each of the bridge side chain links, analogue to digital converters encapsulate the sensor measurements and publish them via IP to a server located at ground level in one of the nearby toll houses. The displacement transducers are functional to calculate the friction coefficient: in fact, the FE model cannot generate a coefficient of friction (the 'feature of interest'), because the model has no visibility of the saddle displacement, although able to estimate the force. The strain gauge provides the data necessary to calculate the friction estimation. A WSN deployment removes the need for provisioning wired power and communications on-site by relying on battery power and wireless communications technologies. The WSN gateway will receive the temperature readings and publish them to the local server hosting an InfluxDB time-series database instance.

There are two layers at which the model and data interface: *(i)* the software layer, i.e. the model software's interface through which parameters can be modified, and the model invoked; and *(ii)* the application layer, i.e. the interface at which the link "understands" the received input measurement (e.g. a temperature reading) and send back information about how to adjust the model eventually. Layer 1 enables the functionality of Layer 2. At a software layer, real-time integration between the model and sensors requires each functional block to have a set of computing interface (APIs) through which it can be interacted with. Technical details include that the sensors' API is provided by an MQTT message broker (L2), to which the ADCs and WSN gateway will publish their data. The DT software will subscribe to this data stream and so be passed any measurements received by the broker. Specific software packages that have been used for this purpose in the past are the Lord MicroStrain MSCL Python API, which is able to gather data from wireless sensors and pass it to a message broker.

4.4. Data/model integration

As highlighted in Section 4.1, different types of sensor data are present and need to be integrated. Some examples are: *(i)* recorded temperature data is passed directly into the model (L6) as a set of model inputs; *(ii)* data from the weigh-in-motion machine is given as axle weights, measured before a vehicle reaches the bridge deck and converted into a quasi-static load (L4), with a location estimated from an assumed speed; *(iii)* chain strain measurements are not inputs to be model, but are compared against the modelled strains (L5) to provide validation and updating; similarly, *(iv)* displacement readings are also not entered into the model, but combined with the model strains to generate a figure for the friction coefficient.

To enable this range of functionality, the model requires a sophisticated set of APIs. The DT software must be able to update the FEM by modifying the parameters of interest. For example, data from the chain strain measurements due to temperature change will be informing the friction coefficient at the saddles. Features of interest are returned as software variables that the DT software can access. This study is currently at the exploratory stage and uses a simple software (Midas GEN); however, sophisticated software package such as the OpenSeesPy library allows to build and run models in a Python environment, where features can be modified based on software variables.

Before producing any output, the DT compares the modelled strain values with the recorded value to help provide confidence that the model parameters are correct. This comparison allows the system to generate an uncertainty value for the modelled output. Consistent or systematic discrepancy between the modelled and measured values require the model to update. This updating is based on all the available information since any measurement (or set of similar measurements) could give huge uncertainty, especially for short records.

The DT then combines the strain values with the relevant recorded displacement values to calculate the coefficient of friction for each saddle, which is the feature of interest. These coefficients are recorded in an InfluxDB time-series database so that historical trends can be created and values are presented to the infrastructure management. These different processes are illustrated graphically in Fig. 10.

For the needs of this case study, the twinning rate can be pragmatically updated according to: *(i)* regular maintenance: for routine loads that affects the bridge long-term (such as temperature changes and changes in the saddle), periodic update once a month; *(ii)* exceptional monitoring: hourly, during and after extreme events (e.g. wind storms, heat waves). All the records are kept as the history of the structure behaviour, which could be useful for later further analysis.

4.5. Operation

Although historical records could enable the definition of operational thresholds, in this case study, previous analysis of the rock mechanics gave estimated capacities of the Clifton abutment, hence limits on the loads on the tower, i.e. operational limit on the saddles (O1). Thus, engineering judgment is used to estimate what is a maximum safe

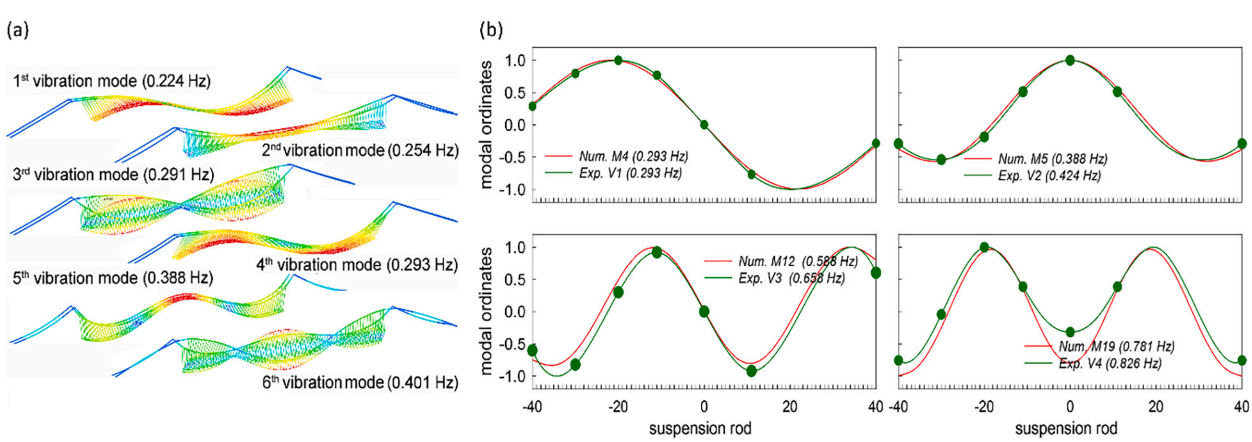

Fig. 9. Some characteristic (a) mode shapes and (b) comparison of numerical versus experimental vertical mode shapes of the CSB model. Elevation view showing deck only.

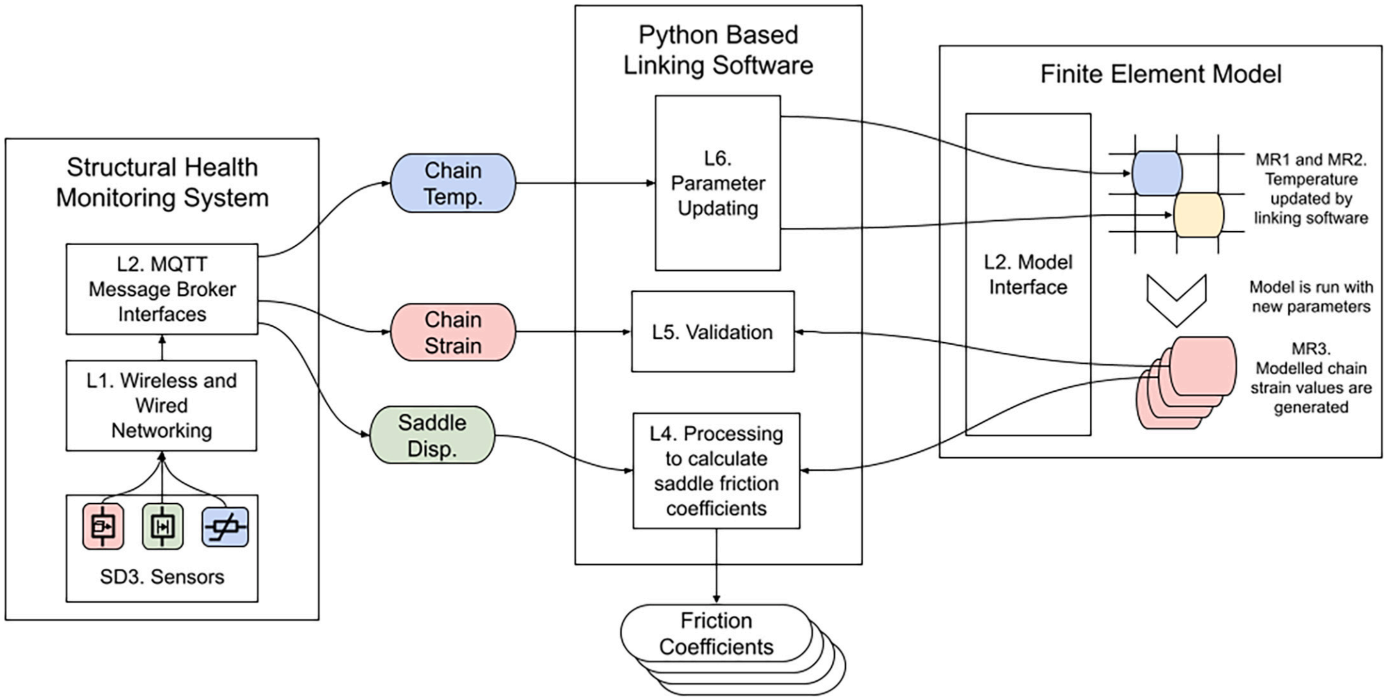

Fig. 10. The DT linking software is only part of the DT. It receives of a range of different types of sensor value, each of which must be handled differently depending on how they support the function of the FEM. The sensors and model make up the other parts of the DT, and components are referenced as in Fig. 3.

strain on the back-span chains, and so at what value of friction action must be taken (E2). The DT can then report real-time and historic friction values and present rates of change, presenting the data through a dashboard (O2). When the operation threshold is reached, a set of predefined actions or alerts are triggered, e.g. for maintenance or inspection of the rollers.

Assuming the friction coefficient increases linearly overtime, the DT would be functional to provide information to infrastructure managers and operators for the maintenance schedule. On the contrary, more complicated scenarios can arise. For example, cold weather could increase the value of the friction coefficient since low temperatures affect the performance of the lubricant (E3). In this scenario, weather forecasting data would allow the DT to predict what value of friction might be expected for those temperatures and allow maintenance to be done while the weather is still warm and access is straightforward.

Data management and sharing (E5) is a delicate process due to privacy issues, and policies are needed to set standards and share data confidently. As owner and manager of the bridge, the CSBT signed a Data Transfer Agreement (DTA) which defines data and DT ownership, exchange and governance, e.g. stating explicitly which sorts of data belong to which organisation. This agreement relates to the contingency of academic research, thus also underpins any wider dissemination of data (e.g. via publication, presentation). In other contexts (e.g. industry), a DT would be run for and by (or under a contract for) the owner or operator, who decides for any agreements they make with any other organisations. Although infrastructure data is unlikely to contain any personal data (so not under the remit of regulations such as the EU's GDPR), it can still be extremely sensitive and not liable to open access.

5. Discussion and future research

This paper represents one of the few detailed workflow for developing DTs in AEC, alongside a practical application for a bridge in the UK, namely the Clifton Suspension Bridge (CSB). The developed methodology includes five steps, which were designed alongside the Gemini Principles to ensure the resulting DT has a clear purpose, is trustworthy and functions effectively. The methodology is broadly applicable in Civil Engineering. The CSB's DT indeed: *(i)* aims to assist bridge managers with saddle performance, operation and maintenance; *(ii)* is built on data of appropriate quality, has a Data Transfer Agreement (DTA; academic context) in place to ensure ownership and appropriate use, as well as openness within the limits of data ownership restrictions; and *(iii)* it is based on a connected environment, has protocols to regulate governance (in the DTA) and a structure able to accommodate technology as it evolves (e.g. embedding machine learning). Nevertheless, some factors (e.g. restrictions on maintenance schedule, budget) are currently outside the scope of the DT and thus excluded from the model, although it is recognised they could have a significant impact on the applicability of the system's output.

Considering Arup's framework [4], the proposed DT for the CSB has the ambition to be classified as a Level 3 DT since it aims to provide predictive maintenance, alongside analytics and insights of component degradation, identify necessary repairs or remedial actions before asset failure occurs. A Level 3 classification is justified as the developed DT demonstrates: *(i)* autonomy, the DT has partial autonomy, and our method proposes a route to full autonomy of decision making although initially engineering judgment is still needed before action is taken; *(ii)* intelligence, the DT is based on historic data for validation/calibration and uses learning to improve response; and *(iii)* the DT is trained using supervised learning, and the labelled data generated when decisions to act or not act are made.

If *Digital modelling* (Step 2) and *Dynamic data transmission* (Step 3) are relatively straightforward in the 2020s, *Data/model integration* (Step 4) definitely remains the most challenging step. The capability of integration drives the choice among the range of available modelling packages, which is informed by Step 1 (*Data and need acquisition*). Midas GEN software was chosen as a pragmatic first step to carry out exploratory FE modelling (preliminary mode shapes and boundary conditions), with a view to using OpenSees, which is less user-friendly but more versatile. OpenSees, as other software, in fact, can be implemented into a Python environment (OpenSeesPy) for full integration and "right-time" analysis. Assuming this software integration, deriving maximum value from it can still be very challenging depending on the feature of interest. Both sensing and model updating must be targeted to reduce the uncertainty in the modelled parameters, and this is still to be implemented in an entirely autonomous system. As opposed to aerospace, manufacturing or other industry, the DT twinning rate in AEC could vary according to the purpose: for example, a monthly update could suffice for maintenance monitoring purposes (e.g. degradation rate), while more frequent updates could address the structure behaviour during exceptional (e.g. extreme weather) events.

Finally, the *Operation stage* (Step 5) is crucial for the success of a DT. Bridge operators are scheduling activities as a matter of course, and maintenance is one of the activities that a DT can support in an automated and integrated way. In fact, a work schedule (or other restrictions) could integrate input data, so the DT can timetable the saddle maintenance when it is optimal. It has been suggested that the 5th Industrial Revolution will move from cyber-physical systems to human-centric or human-in-the-loop systems ([71,72]]. In many ways then the type of DT discussed here, whereby a virtual model based on real-world data informs human actors' necessary decisions and interventions on the physical asset, is well aligned with the value-centric Industry 5.0. This concept links to discussions around semi-automated DT systems to inform asset maintenance in fields such as wind turbines [73], but presents challenges in how Industry 5.0 for civil infrastructure management aligns with DT's Levels 4 and 5, which aim for increasing degrees of autonomy, and crucially, how the potential value of a purposeful human-in-the-loop DT is determined and fully exploited.

This study was research-based; therefore, no business case was behind it to justify the effort/investments. However, it is recognised an assessment of costs and benefits is crucial for practical applications. The Value of Information and business models may help to understand how a DT generates value so that costs and returns justify the scope and development of the DT. DTs can provide information to asset owners and managers for improving the operational efficiency associated with the asset's condition and its lifecycle. For example, they can provide a better understanding of asset risks by detecting anomalies and predicting the asset behaviour; or, they could support maintenance optimisation, enabling scheduled maintenance which anticipates and prevents component failure. However, there is currently little guidance for identifying and capitalising on the wider business opportunities associated with this technology beyond cost savings and operational efficiencies.

In addition to the realisation of the added value (i.e. reducing cost or some other benefit), operators and owners also have to gain confidence in DTs, when moving away from standard practice. The use of DTs must earn the trust of infrastructure managers, and this can be done by developing a track record of successful demonstrations. This process takes time, requiring a certain amount of buy-in from the infrastructure managers using the tool. The development and application of a DT will also require a cultural change, supporting and driving stakeholders to move from what they have always been comfortable with (e.g. drawings, design models) into this new environment (e.g. integrated multi-disciplinary 3D models).

This study presents a general framework for DTs in Civil Engineering and applies it to a case study of an existing bridge in the UK (Clifton Suspension Bridge, CSB); the preliminary stage of the DT that we are developing uses the saddle friction issue of the CSB as a demonstration. This study is just an example and is intended to inspire more general DTs for broader operation and maintenance (e.g. buildings, wind turbines, etc.). Within this case study, further development will focus on defining further operational thresholds (e.g. wind conditions) and how data is presented to stakeholders to best support decision-making, e.g. automatic notifications. Despite this case study's focus on the saddles, the potential of the CSB's DT is vast. There are other current measurements (e.g. traffic counts and extensometers in the rock, as well as periodic inspections) that could be exploited for further studies. For example, this data could be used to simulate impact from adverse weather events, providing targeted guidance for managers, first responders and infrastructure owners (e.g. fatigue from wind and traffic loading). Finally, this study relates to a case of existing (legacy) infrastructure; future research could also focus on DTs throughout the entire lifecycle of infrastructure [74].

Research and application of DTs in AEC have a rich agenda for the future. In the short-term, this study could be extended by applying the workflow to another case study, e.g. a building or another bridge. In the medium-term, the DT could include machine learning and AI to learn efficiently from various sources of data and detect anomalies. The ability to use that learning for autonomous decision making would improve the DT's sophistication to a Level 4. In the longer-term, it is evident that no single DT will be sufficient for modern complex cities: in a smart city scenario, independent DTs of various assets will need to communicate and cooperate, providing feedback to a central decision making "hub" or city-level decision makers. For example, the DT of a particular asset (e.g. a bridge) could be federated with the DTs of other related assets (e.g. roads). This advancement would qualify as a Level 5 DT. Finally, the fundamentals of the proposed workflow could be combine with other elements related to human health, safety and well-being, environmental sustainability and disaster/climate resilience. For example, a DT of an asset of interest (e.g. a building) could be used to analyse its characterstiis in relation to users' health and wellbeing, by means of immersive reality and other tools.

6. Conclusion

The concept of Digital Twins (DTs) has the potential to radically change the design, production and maintenance of assets; however, more research is needed in order to accelerate the digital transformation in the Architecture, Engineering and Construction (AEC) sector. This paper has developed a five-step workflow process for building DTs in the built environment, aligned with the current DT state-of-the-art (e.g. Gemini Principles): data and need acquisition (1), digital modelling (2), dynamic data transmission (3), data/model integration (4) and operation (5). The workflow was applied to the Clifton Suspension Bridge (Bristol, UK), which was adopted as a case study. The developing DT had the ambition to be classified as a Level 3 DT since it aimed to provide predictive maintenance, alongside analytics and insights of component degradation, identify necessary repairs or remedial actions before asset failure occurs. In the future, machine learning and AI could provide the DT with autonomous decision-making (Level 4); in the longer-term, this bridge DT could be federated with the DTs of other bridges or related assets (e.g. roads) (Level 5). Some challenges were identified in the development and adoption of DTs, such as its validation and the business case behind it. This paper's importance resides in the knowledge challenge, value proposition and operation dictated by developing a DT workflow applicable to various assets in the built environment, as well as demonstrating the process for a single bridge which ultimately represents a relevant use case.

Data availability statement

All data which is not subjected to non-disclosure agreements with stakeholders or thirs parties are available upon request; data sources are clearly specified throughout the paper.

Author contributions

MP conceived the research work and led this study; SG was responsible for data gathering and data/model integration; EV and RDR developed the virtual model and assisted with data/model integration; NC contributed to the framework and its application for operation; GG contributed to the literature review and methodology; PT and TT conceived the research and obtained funding; JM provided data and advised the work; CT conceived the research and advised the work. All authors contributed to the manuscript text and/or figures and reviewed the final version.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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