Digital Twin Construction

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Abstract

The concept of a 'Digital Twin' as a model for data-driven management and control of physical systems has emerged over the past decade in the domains of manufacturing, production, and operations. Digital twins represent a step change in the evolution of manufacturing, capable of facilitating the implementation of Industry 4.0 principles. In the context of buildings and civil infrastructure, the notion of a digital twin remains ill-defined, with little or no consensus among researchers and practitioners of the ways in which digital twin processes and data-centric technologies can support design and construction. This paper builds on existing concepts of Building Information Modelling, lean project production systems, automated data acquisition from construction sites and supply chains, and predictive analytics to formulate a digital twin mode of construction. It contributes a set of core information and control concepts for Digital Twin Construction (DTC).

Keywords

Building Information Modelling; Construction Planning and Control; Data-centric Construction Engineering; Digital Twin; Lean Construction.

Introduction

The 'Digital Twin' concept for data-centric management of a physical system has emerged over the past decade in the domains of manufacturing, production, and operations (Tao et al. 2019a). The concept "digital twin" was first addressed in 2003 by Grieves (2014) as part of product life-cycle management (PLM). Digital twins are generally understood as up-to-date digital representations of the physical and functional properties of a system, which may be a physical instrument (e.g. an aircraft engine), a social construct (e.g. a stock market), a biological system (e.g. a medical patient) or a composite system (such as a construction project, with aspects of physical products and social systems). Digital twins are considered by some to represent a step in the evolution of manufacturing, capable of facilitating the implementation of Industry 4.0 principles (Rosen et al. 2015; Uhlemann et al. 2017).

Although there is no commonly agreed conceptualization or definition of the term (Gerber et al. 2019; Kritzinger et al. 2018), numerous organizations have defined digital twins in terms of their functions and characteristics. According to Tao et al. (2019b), digital twins have three main elements: a physical artefact, a digital counterpart and the connection that binds the two together. The connection is the exchange of data, information and knowledge between the physical and virtual counterparts, enabled by the development of advanced sensing (e.g. computer vision), internet of things (e.g. interconnected assets), high speed networking (e.g. 5G internet) and advanced analytics (e.g. machine learning) technologies (Gerber et al. 2019; Rosen et al. 2015).

In the academic and popular literature of the built environment, many authors use the term digital twin simply (and naively) as a synonym for BIM models generated in design and construction. Others perceive 'digital twins' as digital representations of buildings, bridges, etc. for the purpose of their operation and maintenance, based largely on the BIM models produced through their design and construction (Aengenvoort and Krämer 2018; Arup 2019; Borrmann et al. 2018). For example, in addition to listing five differentiators between BIM models and digital twins, Khajavi et al. (2019) observed that the use of digital twins of buildings is restricted to building operation.

This paper develops the core concepts for development and implementation of a data-driven digital twin paradigm for the construction of buildings and civil infrastructure. The construction phase presents specific challenges in terms of compilation and operation of an effective digital twin. As project production systems (Ballard and Howell 2003), all significant construction projects require intense collaboration among large groups of independent designers, consultants, contractors and suppliers. Each collaborator generates information about the product and the process of construction. They use a wide variety of digital tools with multiple data formats that are generally not interoperable (Ch. 3, Sacks et al. 2018). The federated building models that construction delivery teams compile are not digital twins: they reflect the as-designed and as-planned states of a project, but not the as-made nor the as-performed states; and they are not updated as the physical state changes. The temporary nature of project sites makes monitoring the developing product and the actions of equipment and workers challenging, whether performed by people or by automated technologies.

Yet digital twins for construction are highly desirable, because effective decision-making concerning production planning and detailed product design during construction, based on well-informed and reliable 'what-if' scenario assessments, can greatly reduce the waste that is inherent in construction projects (Formoso et al. 2002; Gonzalez et al. 2007; Horman and Kenley 2005; Ogunbiyi et al. 2014). This has been recognized for many years in research and in practice. It has spawned broad areas of research, such as Automated Project Performance Control (APPC) (Navon and Sacks 2007), Construction 4.0 (Oesterreich and Teuteberg 2016) and construction applications of technologies for acquisition of as-built geometry, including, for example, photogrammetry and laser scanning (Brilakis et al. 2010; Han and Golparvar-Fard 2017; Yang et al. 2015). Likewise, a plethora of startup companies have emerged in recent years whose *raison d'etre* is to automate data acquisition from construction sites. However, these have been isolated efforts, with no guiding principles, plans or concepts for the role they must play in a coherent 'digital twin' whole. This is the gap that we address.

The goal therefore is to derive a coherent, comprehensive and feasible paradigm for planning and control of design and construction of buildings and other facilities. By its nature, this is exploratory research and the method is conceptual analysis. The purpose of conceptual analysis is to establish “the conceptual clarity of a theory through careful clarifications and specifications of meaning” (Laudan 1978). Together with systematic observation/experimentation and quantification/mathematization, conceptual analysis forms an important part of the scientific method (Machado and Silva 2007), and is focused on breaking down the concepts into elementary parts and studying their interdependencies (Beaney 2018). “These actions include but are not limited to assessing the clarity or obscurity of scientific concepts, evaluating the precision or vagueness of scientific hypotheses, assessing the consistency or inconsistency of a set of statements and laws, and scrutinizing arguments and chains of inferences for unstated but crucial assumptions or steps.” (Machado and Silva 2007).

The paper begins with a review of the key management processes and digital tools that have evolved in the spheres of design, planning and production control of construction projects: Building Information Modelling, lean project production systems, automated project performance control, and Construction 4.0. Building on the background review of these concepts, their benefits, and their limitations, we define the requirements for a holistic digital twin mode of construction. We formulate a set of ontological and epistemological dimensions of digital twins for construction, which we summarise in a set of core concepts. Working from the requirements and the core concepts, we derive a workflow framework for a comprehensive construction digital twin management system.

Background

The paradigm for construction centred on a digital twin builds on the foundations of computing in construction, of construction monitoring technologies and methods, and of lean thinking applied to construction planning and control. These have been the primary foci of research and development in construction for much of the last half century, and each of them has yielded important advances. However, these research streams have remained largely separate from one another. Digital twins offer the conceptual solution to joining these strands in an effective closed loop production control system. We review each of these areas briefly, concluding each with discussion of the ways in which they underpin the new paradigm of construction using digital twins.

Lean Construction

Lean construction prioritises achievement of smooth production flows with minimal variation and thus minimal waste of resources. Its TFV theory adds *Flow* and *Value* conceptualisations of production in construction to the traditional *Transformation* (activity black-box) view (Koskela 2000). As such, Lean construction provides the principles for an effective model of production planning and control that can exploit the information generated by the monitoring and interpretation aspects of the digital twin to optimize workflows.

The primary flow is the flow of work itself, which is usually embodied as locations in a building (Kenley and Seppänen 2010; Sacks 2016). The key supporting flows are those of workers, materials, equipment, and design information. Any interruption of a supporting flow will disrupt the primary workflow. Planning must be proactive and requires increasingly detailed planning actions to identify and remove constraints to prepare tasks in preparation for assignment to crews and execution. Iterative and increasingly detailed planning loops depend on the availability of increasingly detailed process status information, which well-designed monitoring technologies can provide if they are embedded in a suitable digital twin paradigm framework.

Conversely, complete and accurate information concerning the current status of production flows is essential for effective implementation of lean production planning and control systems, such as the Last Planner® system (LPS) (Ballard 2000). This is one of the key potential synergies of lean construction and BIM (Sacks et al. 2010).

The Plan-Do-Check-Act (PDCA) cycle of production control (Deming 1982), a production control technique embraced within lean construction, is of direct relevance for the construction digital twin paradigm. Modern construction planning and control can be understood as a sequence of concentric PDCA cycles (Forbes and Ahmed 2011; Koskela 1992). The LPS itself embodies PDCA cycles at the levels of master planning, phase planning, look ahead planning, and weekly work planning. One of the key challenges to effective implementation of LPS is that the 'Check' step requires comprehensive and accurate information about the degree of fulfilment of the constraints to any activity (including the status of all supporting flows). Obtaining this information is especially difficult at the look ahead level (Hamzeh et al. 2015), and it is here that automated monitoring can be of particular benefit.

Accordingly, construction using digital twins should implement monitoring feedback loops at varying scales of cycle time – from monitoring activities to determine conformance to major project master plan milestones, to near real-time cycles of monitoring material deliveries, locations of workers and equipment, etc. It must also provide prognostic capabilities to extrapolate from current conditions and evaluate the expected emergent outcomes of planned alternative management actions, supporting proactive planning and control.

Building Information Modelling

Building Information Modelling (BIM) encompasses the workflows and the technology for digital, object-oriented modelling of construction products and processes (Sacks et al. 2018). BIM platforms were developed in response to the need for effective IT tools for design, and the processes have evolved to fulfil the need for digital prototyping in construction, allowing testing of both design and production aspects before construction. Many practitioners see BIM as the core technology enabling construction digital twins.

However, so-called 'as-built' BIM or 'Facility Management' (FM-BIM) models (Teicholz 2013) provide information about the status of buildings when commissioned, but they fall short of the digital twin concept of continuously updated representation of the current state of a facility. 'As-built' models are generally compiled reactively, following execution, and their purpose it to provide owners with models for the operation and maintenance phase – called the 'asset information model' in ISO 19650 (ISO/DIS 19650 2018). They are not intended to provide the short cycle time feedback needed for project control.

Furthermore, the predictive simulation and analysis tools available for use with BIM are designed for predictive use in design, not in project execution. Applications for structural engineering, for ventilation and thermal performance, for lighting and acoustics, all provide predictions of future performance of the built product. Critical Path Method (CPM) tools for master planning are used with BIM models to perform '4D CAD' analysis of project schedules, but these are inappropriate for production control (Forbes and Ahmed 2011; Sacks 2016).

While BIM tools provide excellent product design representations, they lack features essential for construction with digital twins:

- their geometry representations use object-oriented vector graphics, which is less than ideal for incorporating the raster graphics of point clouds acquired through scanning;
- the object models of BIM systems lack the schema components for representing the construction process aspects

Furthermore, tools for short cycle predictive analysis of process outcomes, such as those developed in research using agent-based simulations, are lacking.

Construction Monitoring Technologies and Applications

The stream of monitored data that flows from the physical artefact to the digital processes are an essential component of the connection between physical and digital twins. In current traditional construction practice, people monitor the progress of construction work largely by direct observation and measurement, in manual work that is time-consuming and error-prone (Costin et al. 2012; Zhao et al. 2019). Researchers have proposed and tested many technological solutions for automatically monitoring construction work and some have recently become available and applied commercially. Table 1 summarises some of the key technologies investigated for monitoring construction activity.

Table 1. Data acquisition technologies applied to monitoring construction.

Technology	Hardware	Common applications	References
Electronic location and distance measurement	Robotic Total Stations, range finders, etc. Laser scanning	Record current state of construction	(Brilakis et al. 2010a; Han and Golparvar-Fard 2017; Yang et al. 2015)
Global Positioning System (GPS)	Differential GPS readers	Locate and measure work done; track production progress	(Ergen et al. 2007)
Computer vision (stills and video)	Video, stills, 360° images	Safety; production progress; labour and equipment	(Luo et al. 2018; Seo et al. 2015)
Audio and sonar	Microphones	Identify equipment function and use	(Cheng et al. 2017; Lee et al. 2020)
Tag identification systems	Bluetooth Low Energy (BLE), Radio-frequency identification (RFID), Barcodes	Track materials; worker locations and durations; quantity and quality	(Park et al. 2016; Zhao et al. 2019)
Communication networks	Wi-fi, Ultra-Wideband (UWB), cellular	Material tracking; worker locations and durations; safety.	(Teizer et al. 2007)

Technology	Hardware	Common applications	References
Sensors	Temperature, humidity, pressure, strain, rotation	Monitor construction quality; monitor safety	(Annamdas and Rizzo 2010; Barroca et al. 2013; Salehi and Burgueno 2018)

A striking feature of the commercial applications of monitoring technologies (such as those listed in Table 1) to date in construction is that the information gleaned from automated monitoring is generally used in isolated fashion. Almost all have a single subject focus, such as performance of the tower cranes, movement of the workers, or physical progress of the works. there are very few cases of integrated use of more than one technology. Systems installed to monitor the delivery of materials are used only for authorising billing, monitored worker access gates only serve security and safety functions, etc. What is lacking is a cohesive, integrated approach to production control in which multiple monitoring systems inform a project database, which can then support various management functions. Some notable exceptions prove the rule: for example, some collision alert systems employ separate technologies to locate heavy machinery (e.g., GPS) and workers (e.g., computer vision), merging the data to generate actionable information (Fang et al. 2018; Seo et al. 2015).

Navon (2005) proposed such a system, termed ‘Automated Project Performance Control’ (APPC) (Navon 2005; Navon and Sacks 2007) and shown in Figure 1. The key idea was that monitoring could be planned and implemented to feed a centralised database that captured the as-built state of the building under construction. That model could be compared with the as-designed and as-planned information to determine discrepancies, which would directly inform the next round of control, creating a closed loop control system.

However, this proposed system had two major drawbacks. The first is that it was based on the reactive ‘thermostat model’ of control, which is not appropriate for production control in construction (Hofstede 1978). As the flow aspect of production theory in construction reveals, achieving smooth and predictable flows requires proactive filtering of production constraints in advance of assignment of tasks to crews for execution. Reactive correction where actual performance is found to deviate from planned performance is too late to correct a project’s direction; monitoring construction activity retrospectively is insufficient for effective control. The second drawback, related to the first, is that it sufficed with monitoring construction activities, neglecting the feeding flows of materials, labour, equipment information and locations. This reflects the ‘black-box’ transformation view of production in construction and the absence of consideration of the flow view. Proactive management requires monitoring the prerequisite flows of materials, locations, labour, equipment and information that are essential for evaluating the status of constraints, a key aspect of the lean ‘make-ready’ process.

Thus an effective mode of construction control using a digital twin must incorporate a) technologies for monitoring the feeding flows of activities as well as the activities themselves, and b) data processing technologies capable of merging data from multiple streams to compile comprehensive and accurate status information.

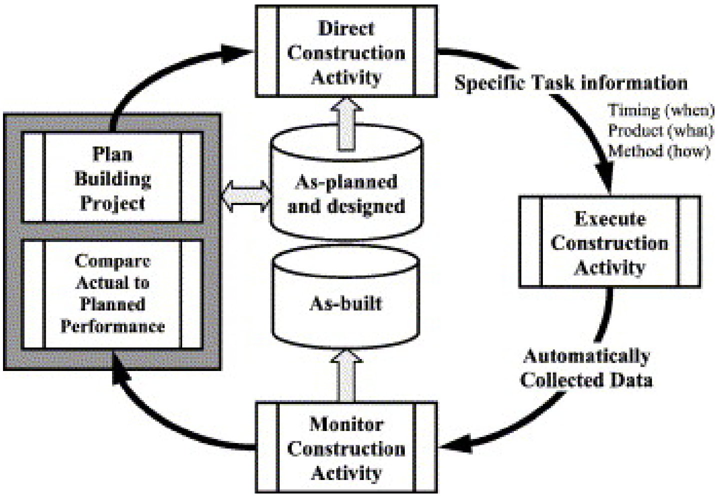

Figure 1. Automated Project Performance Control (APPC) Management Model (Navon and Sacks 2007).

Construction 4.0

Industry 4.0 is the idea that automated production operations can be networked together, enabling direct communication and thus coordination among them, along the value stream, resulting in highly autonomous production processes. The concept defines “a model of the ‘smart’ factory of the future where computer-driven systems monitor physical processes, create a virtual copy of the physical world and make decentralised decisions based on self-organisation mechanisms” (Smit et al. 2016).

Many authors have suggested that the same concept is applicable to the construction industry (e.g. García de Soto et al. 2019; Klinc and Turk 2019; Sawhney et al. 2020). Broadly speaking, ‘Construction 4.0’ is a framework that includes extensive application of BIM for design and for construction, industrial production of prefabricated parts and modules, use of cyber-physical systems (including robotics) where possible, digital monitoring of the supply chain and work on construction sites, and data analytics (big data, AI, cloud computing, blockchain, etc.). However, it is apparent from the descriptions that the understanding of Construction 4.0 falls short with respect to the twin ideas of automation and autonomy of production processes that are central to the conceptualisation of Industry 4.0. The driving principle of interconnectedness and autonomy, of systems that make decentralised yet fully coordinated decisions along automated supply chains and production operations, is absent. In addition, production in construction is still far from achieving even partial automation of operations, which as the focus of Industry 3.0, is a pre-requisite for Industry 4.0. As such, Construction 4.0 offers inspiration, but it does not provide a coherent, comprehensive, and actionable paradigm that can be used as a blueprint for implementation.

Digital Twins in the Built Environment

To date, the digital twin concept has been applied in the built environment exclusively to the operation and maintenance phases. Governmental and other public clients have increasingly recognized that the information provided through use of BIM in the procurement process of infrastructure assets has value in that it can provide the cornerstone for information systems for optimal operation of individual assets, of systems of assets, and indeed of systems of systems

(Gurevich and Sacks 2020). The procedures for defining requirements and for delivery of asset information using BIM for the purpose of asset and system operation and maintenance are proscribed by ISO 19650 (ISO/DIS 19650 2018). In this context, most of the self-declared implementations of digital twins are limited to exploiting building information models (BIM) as information stores and for visualizing information (Bonci et al. 2019; Teicholz 2013).

The UK definition of a 'National Digital Twin'(NDT) – an interconnected ecosystem of digital twins, each modelling a component, a system or a system of systems of buildings and infrastructure, connected via securely shared data – reflects the view of the nature of digital twins in the built environment (Enzer et al. 2019). A set of nine guiding principles, the Gemini Principles, has been formulated to guide development of the UK's NDT (Bolton et al. 2018). While some of the principles are applicable to development of the core concepts for digital twin construction (requirements for value creation, provision of insight, security, quality, federation and curation), others are specific to digital twins in the public domain (public good in perpetuity, openness and evolution). They do not provide the specificity of function that is needed to delineate the requirements for digital twin construction.

In construction, digital twins are a new phenomenon. Boje et al. (2020) reviewed the literature on BIM for construction applications and analysed digital twin uses in adjacent fields to identify gaps, and to formulate and define a "Construction Digital Twin (CDT)". They propose the development of a CDT in three generations. The first generation is described as an enhanced version of BIM on construction sites to date; the second generation introduces semantics, describing CDTs as "enhanced monitoring platforms with limited intelligence where a common web language framework is deployed to represent the DT with all its integrated IoT devices, thus forming a knowledge base"; and in the third generation "the apex of the DT implementation possible to date represents a fully semantic DT, leveraging acquired knowledge with the use of AI enabled agents. Machine learning, deep learning, data mining and analysis capabilities are required to construct a self-reliant, self-updatable and self-learning DT." Despite the authors' thorough review of the state-of-the-art of research and implementation of existing construction applications of BIM, and their consideration in relation to DT developments in other industries, these definitions are not rigorously derived and lack specificity. The key limitations are a) that the formulation of a CDT begins with the conceptual understanding that the CDT is a progression or evolution of the BIM models, and b) that they lack a sound conceptualization of the construction process itself. The latter limitation is most significant: DTC is a holistic mode of construction management, whereas CDT is seen as a technology to support construction as it is currently practiced. The former limitation is a result of the narrower viewpoint.

Introducing Digital Twin Construction

The background review portrays both technological and production management innovations that are making inroads in the construction industry. Yet the innovations pioneered by Construction Tech startup companies are largely applied with a single technology in isolation from other data streams, with little or no integration within any coherent production management paradigm. On the other hand, lean construction offers a sound basis for process integration, but its methods are information and resource intensive and difficult to maintain without supporting information technology. Thus although innovations in BIM, in monitoring technologies and in lean construction are each significant in their own right, there is a need for a unifying paradigm that defines how construction can be managed and executed, one that harnesses these disparate innovations to make effective use of the data and methods they provide. The digital twin concept offers the opportunity to define a new mode of design and production control in construction that comprehensively and coherently integrates the disparate innovations.

Digital Twin Construction (DTC) starts with the recognition that the real-time information streams from the construction project, provided by monitoring and data processing technologies, enable a closed loop model of construction control that has not been possible to date. The PDCA cycle provides the necessary closed loop production control process structure. Figure 2 lists the constituent steps of the PDCA cycle in terms appropriate for DTC. The most significant difference between this approach and current construction control is manifested in the 'Check' phase. If the copious amounts of data that can be collected, from both supply chains and the construction site, using a variety of technologies, can be effectively interpreted to produce accurate and comprehensive information automatically and within short cycle times, then it should be possible to leverage that information, together with the information contained in the project BIM models, to evaluate alternative product designs and production plans.

P	Plan	**Model**	**Digital modelling** of a built facility and of suitable construction plans using BIM technologies and processes
D	Do	**Build**	Fabrication and construction, off and on site
C	Check	**Monitor & Interpret**	**Digital monitoring** of the facility through its construction and operation **Intelligent interpretation** of the monitored data to generate information describing product and process status and the patterns of performance
A	Act	**Evaluate & Improve**	**Evaluate** product design and process plan alternatives **Improve** design, construction and operation by making actionable decisions and applying them to the current digital models

Figure 2. Constituent components of the CDT paradigm with correspondence to the PDCA cycle.

The benefits of such 'data-centric' construction management arise from the significantly better situational awareness that it can provide construction managers and workers at all levels, making construction management more proactive than reactive. Situational awareness is not limited to comprehensive understanding of the current state, it encompasses knowledge of the probable consequences of decisions concerning future action, gleaned from extrapolation using digital simulations and other analysis tools (Endsley 2016). Such foresight applies in concentric PDCA loops at different time scales:

- At the lowest resolution, remote sensing can support crews directly in closed loops. For example, live scanning of the location of a large prefabricated component can be compared with its design intent location in the BIM model in real-time to help guide crews to position it correctly. Real-time monitoring of worker locations can enable delivery of safety alerts when they may be exposed to hazards.

- Continuous monitoring of construction resources on and off site can identify the status of the constraints that govern tasks before the tasks are released into production, such as interdependence between crews, inaccurate product features, availability of space, supply chain status, etc. Managers can then focus on the make-ready process, proactively avoiding situations where crews wait for conditions to mature rather than solving them reactively.
- Daily feedback using AI software for early detection of deviations between the as-designed and as-built product can shorten reaction time, so that issues can be identified and dealt with before they become problems. Evaluation of the current state in comparison with the intended state at any point in time involves value judgements and must answer questions relating to product (e.g. "Is the wall in the right place and of the right dimensions? Is the wall built of the right materials, and are the necessary openings present?") and relating to process (e.g. "Are the wall masons in the right location for their current task? How long do they wait for materials? Is the task ahead of, on, or behind schedule?").
- At periodic planning intervals, possible outcomes of alternative changes to construction planning can be evaluated with agent-based simulations using the current situation as a starting point. Any residual uncertainty in planning, physical conditions, work rates, and decision variables can be modelled probabilistically, so that any complex alternative plan will result in a probability distribution of its outcomes, but the more accurately the status is known, the narrower the range of predicted outcomes will be.
- At the longest resolution, the information accumulated in digital twin construction archives of completed projects will provide an invaluable resource for continuous improvement. Monitored data will enable machine learning to improve the performance of automated tools for interpretation of project status and for prediction of future outcomes. It will also provide a much-needed resource for evidence-based construction management research.

Figure 3 outlines possible causal links between improved situational awareness, on the left-hand side, and the potential benefits, on the right-hand side, assuming DTC.

Figure 3. Possible causal relationships between monitoring, situational awareness, and desired outcomes in construction that can be achieved through the BIM2TWIN approach.

Core Information and Process Concepts

What are the principles that guide design of a system workflow for digital twin construction? Clearly, information and communication technologies play an important role in the development and implementation of digital twins (Tao et al. 2019b). However, the design of new digital twin processes and technologies for construction requires holistic thinking: the ontological and epistemological dimensions of digital twins for construction, the basic information and technology elements, the relationships between them, and their individual and collective functions must be clarified. This is the subject of this section.

Ontologically, a digital twin is a categorization of different information entities of production. Fujimoto considered manufacturing a flow of design information, in which productive assets are seen as information carriers, embodying design information (Fujimoto 2007, 2019). Design information, based on the axiomatic design theory, is structured information of customer characteristics, functional requirements, design parameters as design solutions and production processes (Suh 2001). Largely, the information entities can be classified as belonging to product or process, intended or realized, and virtual or physical aspects.

Epistemologically, digital twins are used by people to design and plan production systems, and to generate new knowledge by comparing monitored data against the designed and planned. This is manifested in the PDCA cycle, embodied in the different functions of production management, including production system design, production system operation (planning, execution and control) and production system improvement (Koskela 2020). Modelling, simulation and analysis facilitate learning as predicted outcomes can be compared with actual outcomes.

Below, we identify four dimensions that define the conceptual space for the information used in the digital twin construction workflow. By stating these dimensions explicitly and then working from them to design the workflow, we seek to ensure that the resulting systems, once implemented, will provide the full breadth of functionality needed to support the DTC paradigm.

Physical – Virtual Dimension

Information is generated and exists in both the ***virtual*** and in the ***physical*** worlds. People generate virtual information in design and in planning to represent intent, i.e. to guide action that transforms things in the physical world. Physical information is inherent in the building or infrastructure, in the components and in the relationships between them, and in the flows and actions of the resources that construct buildings and infrastructure (workers, equipment and material). Information is implicitly present in the length of a window, the elevation of a floor, the material of a beam, and the physical relationship of 'structural support' inherent between a column and a slab it supports. These can be monitored or measured, resulting in digital copies, which are also virtual information.

Floridi (2013) defines four types of information: a) Information about something, b) information as an artefact, c) information for something, and d) information in something. Table 2 lists the four information types and provides examples from construction. Design and planning information is generated by people and exists in the virtual world. These are types (a) and (c). The building itself embodies information of type (b), which exists in the physical world. Likewise, the movements of resources employed in construction embody physical world information, but of type (d).

Table 2. Digital and physical construction information according to Floridi's four information types.

Information type	Construction information	Source
a. Information about something	Product design information: design compiled in BIM models or documents and drawings	Virtual world
b. Information as an artefact	Functional and behavioural relationships inherent in the building; building components' material properties, dimensions, etc., all of which can be measured or monitored	Physical world
c. Information for something	Process plan information, compiled in a construction plan or within the BIM models	Virtual world
d. Information in something	Movement of workers, equipment, materials	Physical world

The digital twin must contain or represent all of the virtual information, comprising both the sets of intended states that exist in people's minds and the sets of actual states that reflect the physical information as it develops through time. When something is changed in the physical world, the current virtual copy of the physical information no longer represents the physical world correctly, unless and until it is refreshed through renewed monitoring or measurement, and this has important implications for sampling frequency.

Product – Process Dimension

Information in the digital twin describes both construction ***product*** and construction ***process***. The product information is stored in the design BIM model's objects, their properties, and their relationships. The process information is stored in the construction plans, including construction methods, schedules (tasks, activities, resources), budgets, etc. Speaking broadly, the term PIM (Project Information Model) defined in ISO 19650 (ISO/DIS 19650 2018) can and should include both product and process. Whereas most BIM tools only provide product modelling (Sacks et al. 2018), management BIM applications, such as VICO (VICO 2016) and Visilean (Visilean 2018), incorporate both product and process aspects.

Recognizing the dual aspects of product and process enables a more detailed elicitation of the PDCA cycle for DTC, as shown in Figure 4.

		Product	**Process**
Plan	**Model**	Design: modelling the building product using BIM authoring and detailing software → *design model*	Planning: modelling the construction process using construction planning software → *construction plan*
Do	**Build**	Delivery of BIM information directly to site Digital fabrication	Procurement Look-ahead planning and task maturity assessment; make-ready process Production control - delivery of directives and of process status information
Check	**Monitor & Interpret**	**Monitoring** quality: using remote-sensing and imaging technologies, IoT sensors, etc. **Analysis** of **all data** to determine product conformance → *as-built project status*	**Monitoring** resources (crews, equipment, safety, etc.) **Analysis** of **all data** to determine process conformance → *as-performed project status*
Act	**Evaluate & Improve**	Design changes → *design model V[i+1]*	Plan changes → *construction plan V[i+1]*

Figure 4. Detailed construction phase Plan-Do-Check-Act (PDCA) cycle and the constituent digitalised parts of the Digital Twin Construction paradigm, showing both product and process aspects.

Intent – Status Dimension

Information describing product and process changes through time. Design and planning decisions expressing intent are made along a timeline as designers and planners propose, tst and refine their formulations. Information representing the physical world changes as work is done and materials are transformed into products and as resources flow through construction processes. As such, each item of information must be associated with a timestamp or version descriptor. Fujimoto and others' information flow-based view of manufacturing emphasizes the fact that information progresses and changes through time. Indeed, a design-information view of manufacturing "is broadly defined as firms' activities that create and control flow of valuecarrying design information […] through various productive resources deployed in factories, development centers, sales facilities, and so on” (Fujimoto 2007, 2019).

The present time (or the ‘status time’, i.e. most recent time when the physical information was monitored and recorded) divides past states from future states. However, it is more practical to classify future states of a design as the design ***intent***, and past states of a product as the product ***status***, because past versions of a design, whether executed or not, become ‘past perfect’ reflections of a formerly intended future state.

a. All information about the *future state* (ex-ante) of a building is expressed in the design and in the construction plan for the parts of the building that have not yet been built. We will call this information the **Project Intent Information** (PII), representing the *as-designed* and *as-planned* aspects of the project. As time progresses, versions of this ‘future state’ are stored. Thus we may have an as-designed model version that was a valid future-looking view at any specific time in the past; likewise, we may store an as-planned construction plan that must be associated with the as-designed model at the same point in time.
b. All information about the *past state* (ex-post) of a building and its construction process records what was done and how it was done. This is the *as-built* product and *as-performed* process information. For example, the location and exact geometry of a wall as it stands after construction are its as-built information, whereas the start and end times and the number of hours a mason worked to build the wall are its as-performed information. Here too, we store multiple versions of the state of a building project over time, and each version is time-stamped with the date and time at which it was measured. We call this information the **Project Status Information** (PSI).

We consider all the information, both planned future versions and measured past versions, to be part of the digital twin for construction. Figure 5 lays out the information aspects of the domain within the three-dimensional space defined by the digital – physical, the product – process and the intent – status dimensions. The two left-hand ‘boxes’ represent the physical twin, while the four on the right-hand side are the conceptual components of the digital twin, including both PII and PSI.

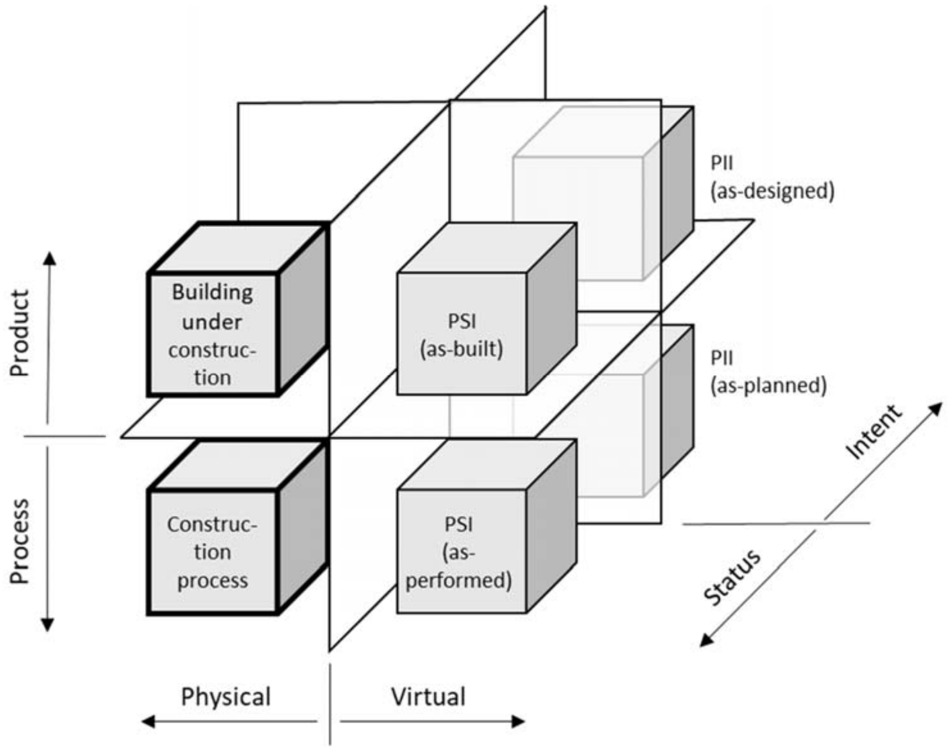

Figure 5. Information aspects of the domain within the three-dimensional space defined by the digital – physical, the product – process and the ex-ante and ex-post dimensions.

Figure 6 shows a simpler 'top view' version of the same space, highlighting the physical – virtual and the status – intent dimensions. In this view, a physical 'mock-up' or scale model of the design intent is shown in the top-left quadrant.

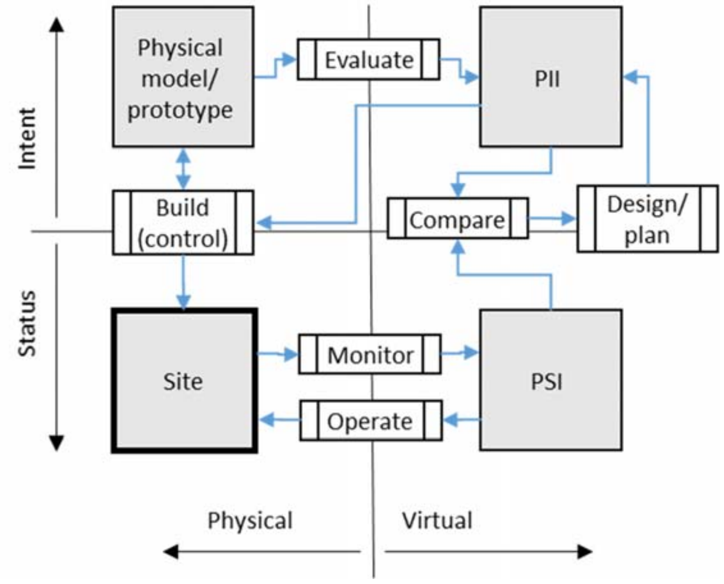

Figure 6. Top view of the three-dimensional space, showing the virtual – physical, and the status – intent regions. The PII, PSI and the site each have both product and process aspects. A physical mock-up or model is shown in the top-left quadrant.

Data – Information – Knowledge – Decisions

To accurately conceptualise digital twins for construction, we must define our use of the terms data, information and knowledge. Up to this point, the discussion has been limited to information. This requires elaboration, because digital twins generate, derive, store and manipulate data, information, and knowledge to support decision-making about product design and process plan before and during construction. Distinguishing among these is essential because the terms determine our understanding of the semantics and of the uncertainty inherent in the different aspects of the DTC workflows.

Broadly speaking, ***Information*** is compiled by interpreting ***data***, information is processed to create ***knowledge***, and knowledge supports ***decisions*** (Kitchin 2014). Despite the broad interest in science, technology and society in general in the fields of information and communication technologies, there is no consensus about the nature and meaning of data, information and knowledge (Adriaans 2018; Castells 2010). Floridi (2013), for example, argued that because information is used “metaphorically and at different levels of abstraction, the meaning is unclear”. However,

Kitchin (2014) argued that data refers to those elements that are ‘taken’ (derived from the Latin “*capere*”), for example, “extracted through observations, computations, experiments, and record keeping” (Borgman 2012). “As such, data are inherently partial, selective and representative, and the distinguishing criteria used in their capture has consequence” (Kitchin 2014). In our context, the data are collected from sensors and other monitoring equipment on the construction site and from the information systems of the companies engaged in construction. They are both qualitative and quantitative, structured, captured, primary, and of all three types.

In some sciences, information is defined as ‘data with meaning’ (Floridi 2019). Floridi (2013) identified three types of information: **physical or factual** (information as reality, e.g. fingerprints, tree rings), **instructional** (information for reality, e.g. algorithms, commands) and **semantic** (information about reality, e.g. train timetables, maps). Value from information is captured through the information life-cycle: **Occurrence** (discovering, authoring), **transmission** (networking, retrieving), **processing and management** (collecting, validating, indexing, classifying), and **usage** (monitoring, modelling, explaining, forecasting, learning). Through the latter three stages, processing, management and usage of information, valuable knowledge can be created.

The immediate outputs from tracking technologies, scanners, cameras and sensors of various kinds are signals that are registered as data. The data in and of itself has little value – it must be interpreted, processed, compared with other data and other information, to allow deduction and induction of useful information (Floridi 2013). Data from any one source is often limited in scope, incomplete or flawed. Numerous data sources are needed to derive some reliable and useful piece of information. For example, one may need a laser scan of a wall, a set of photographic images of the wall, as well as data about the workers who built the wall, and delivery data for the materials used to build it, in order to determine a wall’s location (both absolute and relative to other components), the amount of time workers spent in its vicinity and their productivity, the dimensions of the wall, or the materials used in its fabrication.

Knowledge is understood in different ways too, depending on the particular viewpoints, assumptions and prescriptions (Kitchin 2014). In the philosophy of science, the field of *epistemology* is dedicated to understanding how knowledge is created and disseminated through systems of human inquiry (Steup 2018). The question is about the relationship between the world of ideas (e.g., theories, concepts, and models) and the external world (e.g., physical phenomenon, practices, observations). From the traditional perspective, functions of knowledge include description, explanation and prediction of the behaviour of phenomena (Losee 2001). However, in the context of productive sciences, knowledge also has a prescriptive function (de Figueiredo and da Cunha 2007). That is, production theories have to also guide the improvement of practices, and provide means to validation (Koskela 2000).

Thus, just as a construction digital twin will require software methods to derive reliable information from data, so will it require software modules to perform value judgements using the information and so derive new knowledge about conformance to design or plan. These modules compare as-built and as-performed information with as-planned and as-designed information (i.e., as shown in Figures 5 and 6, comparing PSI with PII). For example, from information about the wall, one might conclude that it was not built in the right location, or that it was built using the wrong materials, or that it required excessive time. This knowledge supports decision making to change future designs or plans if needed.

Digital Twin Construction Information System

Working from the core information and process concepts, we propose a DTC system information system workflow. Figure 7 lays out the DTC workflow and Figure 8 defines the different aspects of information that serve the workflow. The following paragraphs describe the system's workflow and its components – information stores, information processing functions, and monitoring technologies – according to three concentric control workflow cycles.

Model, Build, Monitor & Interpret, Evaluate & Improve cycle

At the start of any construction project, designers work from a project brief to design a product, such as a building, that can fulfil the owner's functional requirements. This is closely followed, in iterative fashion, with planning how the building will be built. These functions are represented by the *Design product, Plan process* activity at the top left-hand of Figure 7. The information generated is *Project Intent Information* (PII). Designers and planners apply a variety of specialised engineering simulation and analysis software (*Predict performance* in the figure), which use the PII and codified design knowledge to predict the likely performance of their design and their plans. The results are knowledge about the behaviour of the building, collectively called *Project Intent Knowledge* (PIK), and the designers use this knowledge to refine their designs through multiple iterations. Figure 8 shows this process as 'Virtual Design and Construction' (VDC), in which designers and planners progressively compile information over time starting from conceptual design and continuing iteratively through the construction phase and ending with completion of construction. The information encompasses both product and process, i.e. as-designed and as-planned aspects. Multiple versions of both PII and PIK are generated, and each is recorded with an appropriate version identifier. There are many ways to design and implement storage for the PII and the PIK - these will be discussed in the following section. Using the metaphor of human twins, we call this information the *Foetal Digital Twin* in Figure 8.

The construction phase begins with the earlier of the start of prefabrication of components off site or the start of construction activity on site. This is the birth of the physical twin, and at this time monitoring begins to accumulate the data and the information that constitutes the PSM. Contractors use the PII information to guide procurement of materials and off-site components and to control construction of the building itself (*Build* in Figure 7). The supply chain off site and the building works on site embody the physical information that defines the status of the project. Continuing the human twins metaphor, the building under construction, the physical processes executed and the construction resources and equipment, are the *Child Physical Twin*. This represents the whole period of construction, starting from possible prefabrication on site, and ending with handover of the building to its owners. Throughout this period, a variety of monitoring technologies are applied to capture the status of the product and of the process (‘*Monitor’*), and they generate raw monitored data (Figure 7).

As construction progresses and data accumulate, the *Interpret* function applies Complex Event Processing (CEP) to deduce what was done and what resources were consumed in doing it (Buchmann and Koldehofe 2009). The information it generates describes the ‘as-built’ and the ‘as-performed’ state of the project, i.e. the *Project Status Information* (PSI). Events may be classified using rule inferencing or machine learning algorithms. The input includes not only the raw monitoring data from multiple streams, but also the PII information and any extant PSI from previous cycles. It may also draw on external information archived in or drawn from historic building twins. The PII provides direct clues as to what was expected and physically locates intended components, thus narrowing the search space. Similarly, the PSI provides context along the timeline of product and process. The historic digital twin information supports machine learning or case-based reasoning, which may occur offline. In the human twins metaphor, the PSI is the *Child Digital Twin* (Figure 8).

Next in Figure 7, a specialised *Evaluate Conformance* function compares the actual to the intended, the PII to the PSI. These are value judgements because in every case they must use some external preset threshold value to determine whether the degree of discrepancy between PSI and PII is acceptable or requires remediation. For example, a concrete column may be cast with a width that is less than its nominal design width, but that may be acceptable if the deviation is within the predefined allowable tolerance. As such, it too draws on standard design knowledge. While conformance evaluation can be automated using various AI methods, it is likely that this function would solicit user input for value judgements in many instances. The output of this function is knowledge about the projects status, and termed *Project Status Knowledge* (PSK). Appropriate data visualisation tools are needed to communicate the project status, deviations from design intent or production plan, and any other anomalies (not shown in the figure).

At this stage, control of the process reverts to the designers and the construction planners, who can propose changes to the product design or the production plan in response to the status knowledge, thus completing the PDCA cycle. They can use the same specialised engineering simulation and analysis software (*Predict Performance* in Figure 7) to predict the likely outcomes of any possible changes, and thus to compare and select among alternative options regarding changes to the design, to the construction plan, or to both. Any options selected for implementation are added to the PII, generating new versions. The revised PII continues to drive the construction itself, and the planning and control cycle is repeated until completion of the project.

At the end of a project, all of the accumulated information and knowledge (PII, PIK, PSI and PSK) are archived (Figure 7). At the same time, a set of asset information is methodically extracted and prepared for handover to the client, for purposes of operation and maintenance. This is a subset of the information – amongst other things, no construction plant or resource information is carried through to the asset model. The deliverables to the client, as shown in Figure 8, are the *Adult Physical Twin* and the *Adult Digital Twin*.

Real-time Feedback for Safety and Quality Control

The next PDCA cycle is the real-time feedback cycle, in which information is fed directly from the PSI to managers and workers on site (Figure 7). This includes quality and safety monitoring, where workers must be alerted to any deviation from design intent or from safe behaviour during their ongoing operations. Technologies that sounds alarms to alert workers to imminent potential collisions or falls belong to this category (e.g. Cheng and Teizer 2013). The use of laser scanning to guide the precise positioning of steel cable anchor inserts in bridge piers as they are placed using a crane, prior to casting concrete, is an example of real-time feedback for quality control (Eastman et al. 2011).

Long-term Feedback for Design and Planning

Finally, a broad PDCA cycle exists where each project is viewed as a design-construction event, after which the digital building twin information is archived and subsequently used for organization- or industry-level learning (‘check’), with improved action following in subsequent projects. The learning will manifest in a variety of ways:

- DTC archives provide a source for labelled data to support training of machine learning applications, such as classifiers for complex event processing of monitored data. A caveat to such use is that it requires some or all of the raw monitored data, which may or may not be archived.
- Design intent information encapsulated in BIM models, together with associated records of the outcomes of performance simulations (the project intent knowledge) may be used as a resource for case-based design;
- Researchers may use the wealth of data recorded in DTC archives, subject to appropriate guarantees of privacy and security, to pursue empirical, evidence-based research on subjects such as production management strategies, supply chain performance, construction safety, labour productivity, and a host of other topics. The availability of massive, accurate, reliable and accessible data sets represents a complete change for construction researchers who currently struggle to collect meagre data sets from active construction sites.

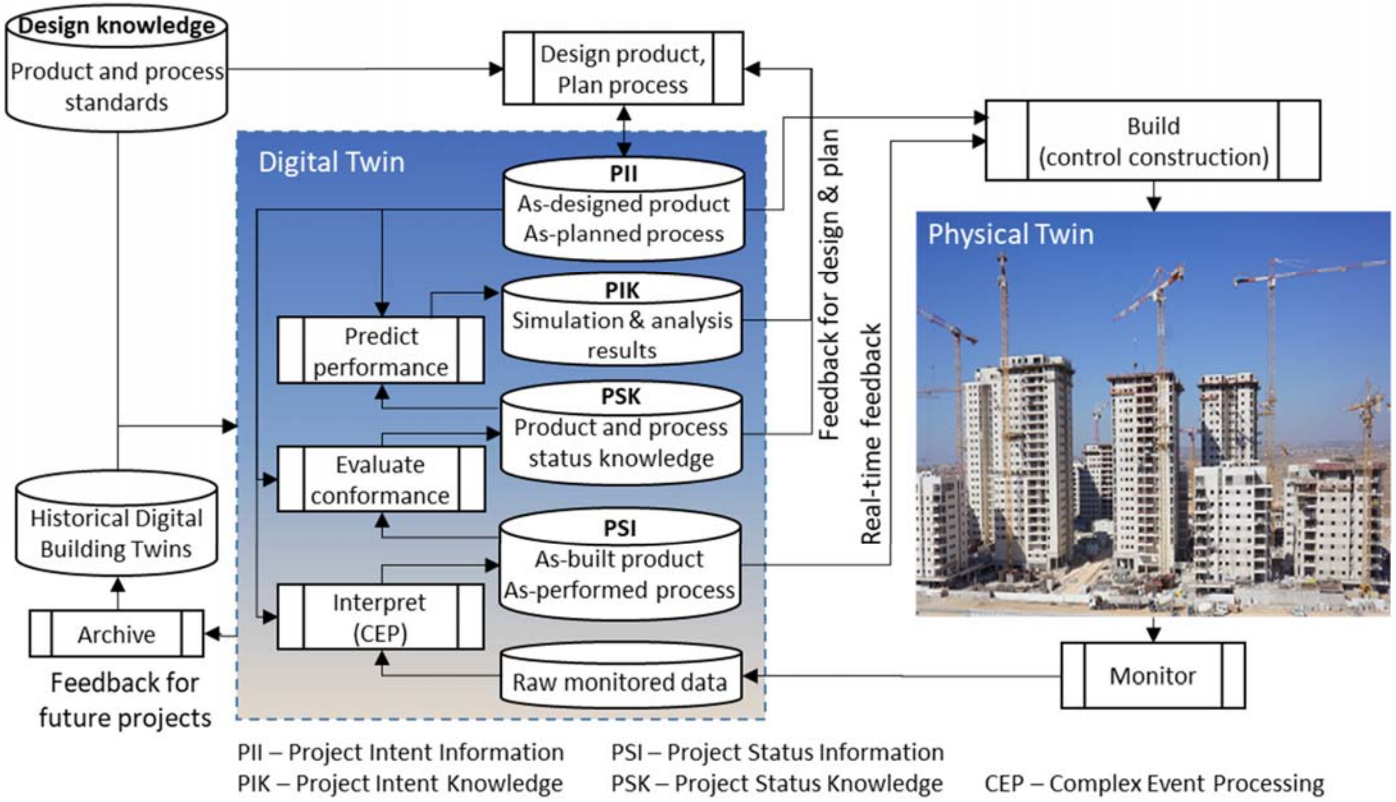

Figure 7. Digital Twin Construction Workflow Process

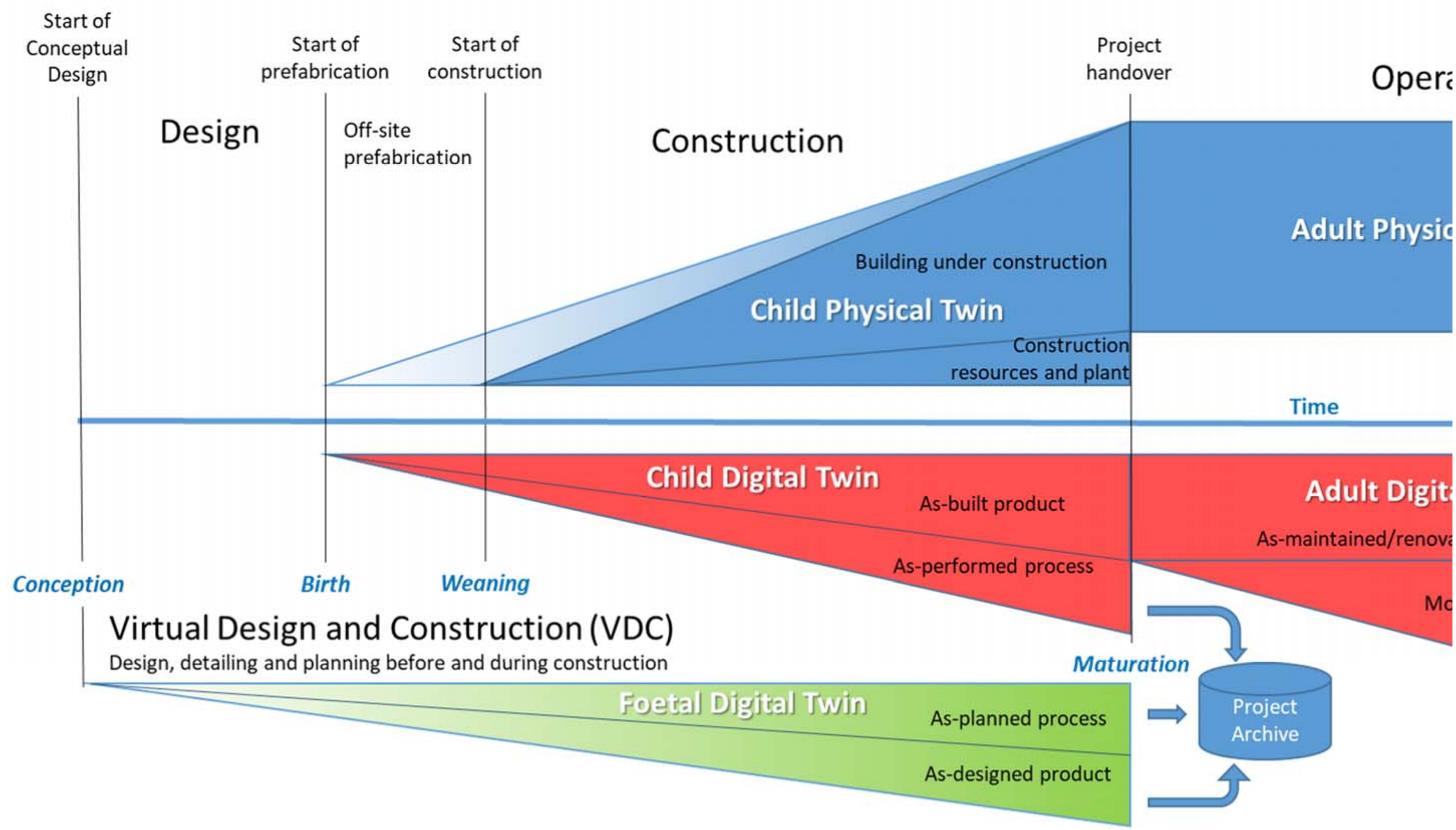

Figure 8. Lifecycle of the physical and digital building twins.

Discussion

Data-centric Construction

The key differentiator of DTC from current models is that it is information- and data-centric. Project intent information and knowledge, data streams from monitoring technologies, project status information and knowledge, are all generated within the system and made available to support decision-making in a set of concentric closed-loop planning and control cycles of increasing time resolution.

Appropriate curation of this data, information and knowledge will make it accessible to AI tools for interpretation, analysis, simulation and prediction. Some of these tools will automate functions currently implemented by people (such as planning, coordinating, communicating, measuring, checking, inspecting), thus either augmenting them or replacing them. Others will implement functions that are currently too labour-intensive or complex for people to do and are therefore not a part of current construction management practice (such as fine-detailed monitoring of equipment and work, or optimization of construction schedules). The degree of automation possible is likely to increase as the information infrastructure is improved, and vice versa.

Comparing DTC and ISO 19650 concepts

Part 2 of the ISO 16950 standard (ISO 2018) formalizes the information flow processes for buildings and civil engineering works when using BIM. It is the culmination of long-term development that originated with the UK BIM task group in 2010 and has gained acceptance throughout the world as the governing paradigm for information management in construction. In terms of the standard, information for execution of a construction project is collected in a Project Information Model (PIM), which incorporates the building models (BIM), the project execution plans and any and all information collected during project execution. As such, the PIM encapsulates all of the PII, PIK, PSI and PSK defined in the context of the DTC, but it does not distinguish among them.

A second, and more significant, difference between DTC and the ISO 19650 process is that whereas ISO 19650 lays out a mode of information flow, DTC prescribes a comprehensive mode of construction planning and control. The boundaries of DTC in Figure 7 incorporate not only the information components but also the information processing components themselves.

The scope of the DTC, like that of the PIM, is restricted to the design and construction phase, distinguishing between the ‘child’ and ‘adult’ forms of the digital twin (see Figure 8). ISO 19650 defines an Asset Information Model (AIM), which is extracted from the PIM when a building is handed over to its owner and contains the information required for operation and maintenance (O&M). In the DTC mode, the information needed to prepare the foundations of a digital twin for O&M will be drawn primarily from the PSI.

Database Structure

The design of the database structure for the DTC data, information and knowledge is a highly unconstrained problem and many alternative configurations are possible. Whereas current modes of data storage in construction projects almost exclusively consider file-based storage, object-based graph networks stored using cloud services are likely to be preferable for DTC. The reason is that aspects of PII, PIK, PSI and PSK may overlap and share common resources and/or data at the object or at the property levels. Some examples:

a) An architect designs a door and models it as an instance of a door class with appropriate property values in a BIM model (product PII). Once the owner approves the door design, one of its meta-data properties is set to “approved for construction” (process PII). The contractor uses the BIM model for procurement, and a value of “purchased” is set for the instances’ status property set, together with a timestamp of the transaction - this is process PSI. Later, an inspector (or a smart software agent) compares the door installed to the design intent confirms that the door installed meets the design intent and sets an “approved” value and timestamp for the inspection status property set – this is PSK. In this example, both the intent and the status information and knowledge is associated with the same single BIM element instance.

b) Consider the same example of a door design intent expressed as a BIM element instance. However, due to the large size of the door, the contractor decides to procure and install the door in two parts. This necessitates modelling of two new instances of the door “as-procured” (later to be designated “as-built”). Assuming that the two parts fulfil the original design intent, this is not considered a change and no update of the intent information is necessary. In this case, the PII and PSI are modelled as different object instances. Comparison of the PII element with the two PSI elements will yield the determination of fulfilment (or not) of the design intent, thus filling in PSK as before, but this time in the distinct “as-built” instances. In this example, the intent and the status information are associated with separate BIM element instances.

c) Where file-based storage is used, it will be more common for the contractors to generate their own BIM models for construction. These may be modelled from scratch or initially copied from the design intent models, but in any case, the PII and the PSI are stored separately. While they can be associated with common IDs or by location, they carry their own property sets, with potentially overlapping values that may be changed independently.

d) During initial design, or during construction, an engineer prepares a construction plan using 4D simulation software and an optimization engine. The input to the plan includes the planned tasks (process PII) and their related BIM elements (product PII). The output of each run of the analysis is a set of predicted outcomes (process PIK). In a file-based system, each task would be replicated in each output file. In a graph-based system, each task object could more simply be associated with a result property set for each outcome, with the property set labelled with an appropriate version number.

Each of these examples represent different configurations of the data storage. This is not an exhaustive set, and there are likely numerous additional configurations and permutations of them. The results of other research suggest that property graph representations with late binding schema objects are apparently most appropriate (Sacks et al. 2020).

System of systems

The digital twin of a construction project will function within a network of digital twins. In eventual implementation, twins of construction equipment – a tower crane, for example – send information to and receive information from the construction project twin. Similarly, the construction project twin itself communicates with higher-order twins, such as that of the local transport network and a concrete batching plant, to determine expected arrival times of concrete mixers.

Platform business model

In many industries, platform business models have proved to be effective for offering products or services with great variety while benefiting from the economies of scale of the underlying platforms. In construction, general contractors, such as the 'Tier 1' contractors in the UK, essentially function as platform organisations. They provide management and coordination services with a lean core of management and administrative staff but rely on subcontracted supply chain partners to provide construction personnel, equipment and materials. However, their growth is constrained by the need to provide core management, which has limited capacity and is difficult to scale. Application of the platform business model in building construction has been proposed (Mosca et al. 2020), including adoption of platform organisations in the context of construction management services delivered by startup companies as 'software-as-a-service' solutions (e.g. Laine et al. 2017), and product platform models in house building (Jansson et al. 2014).

The basis for DTC is a system that integrates monitoring hardware, cloud data storage and sophisticated information processing capabilities. Implementing, maintaining and operating a DTC system will require larger scales of resources than most general contractors can muster. However, the basic components of the DTC are invariant with construction project type, and it is therefore ideally suited to provision to multiple construction projects as an integrated hardware/software service. As such, DTC could be delivered in a platform business model, in which a large DTC platform company provides all of the management, planning and production control infrastructure for general contractors.

Over time, a platform DTC provider could concentrate purchasing from the supply chain, because the service would already aggregate the day to day coordination of subcontractors and supplier deliveries across multiple projects. According to the Portfolio-Project- Operations (PPO) model (Sacks 2016), the ability to coordinate operations across a large portfolio would allow a DTC platform provider to achieve significantly better production flow than general contractors can when managing isolated projects.

The deepening transformative impact of digital information on project delivery models in construction is already clearly evident (Whyte 2019). Against this background, it is quite likely that fulfilment of the DTC mode will also change the current paradigm by facilitating a platform economy in the construction industry. DTC platform companies will offer optimized design and construction management services that surpass the current capabilities of general contractors, and they will control the most valuable part of projects – the data and the information. In theory, this could not only lead to reduction of production management personnel on construction sites, but also to the redundancy of traditional gatekeeper organizations (in this case the classical general contractor), completely changing the way in which design and construction is managed.

Conclusions

Digital Twin Construction is a data-centric mode of construction management in which information and monitoring technologies are applied in a lean closed loop planning and control system. This work applied conceptual analysis to derive the core information and process concepts that will define future development of DTC systems for the design and construction phases of buildings and infrastructure facilities.

DTC should not be viewed simply as a logical progression from BIM or as an extension of BIM tools integrated with sensing and monitoring technologies. Instead, DTC is a comprehensive mode of construction that prioritises closing the control loops by basing management decisions on information that is reliable, accurate, thorough and timeous. That information is provided in two key ways: a) continuous monitoring of the status of design information, supply chains and conditions on site coupled with complex event processing to deduce current status, and b) extensive use of data analytics and engineering simulations to evaluate the probable outcomes of alternative design and planning decisions. Thus, decisions are made within a context of situational awareness. Eventually, people may increasingly rely on the reliability of the recommendations of software agents that recommend courses of action and allow them to direct work autonomously – coordinating delivery of materials, delivering design information, coordinating construction schedules with trades, filtering tasks for readiness and instructing crews to commence tasks. BIM and monitoring technologies play a role in modelling building information and acquiring raw data, respectively, but they are subsumed in a system that exploits data, information and knowledge to provide comprehensive situational awareness.

The DTC process incorporates four distinct Plan-Do-Check-Act cycles at different time resolutions, from real-time feedback from monitoring technologies to workers for safety and quality control, to long-term feedback from archived project digital twin information through machine-learning and case-based reasoning to ongoing projects. The DTC information system comprises five conceptual information clusters of project information: Intent Information (PII), Intent Knowledge (PIK), Status Information (PSI), Status Knowledge (PSK) and monitoring data.

Formal classification of the data, information and knowledge at this high level of abstraction is necessary for development of the analytical and AI tools that can exploit it. In such a data-centric system, the semantics inform consumers (people or software agents) of the intent and the level of confidence of the information. On the other hand, the classifications do not constrain the variety of possible paths for technical implementation of data storage mechanisms for the digital twin. Among possible alternatives schemes: file-based services in which each of PII, PIK, PSI and PSK are stored in distinct file sets; object-based services in which BIM elements encapsulate both PII and PSI in common objects with differing attributes or property sets; object-based services in which BIM elements are replicated for PII and for PSI; and linked data services in which information of all kinds is stored in property graphs, with metadata for each instance defining intent, version and timestamp. The results of other research suggest that the latter scheme appears to be most appropriate, particularly for AI applications including pattern recognition and machine learning.

Traditional construction environments are less controlled, less stable and less homogenous than manufacturing or operation settings, with less predictable patterns and behaviour. Monitoring construction progress, quality and safety has relied on human inspection and interpretation of the current situation, and this hampered, if not entirely prevented, effective closed loop planning and control. DCT contributes by integrating automated monitoring, interpretation, analysis and prediction, providing for the first time thorough situational awareness in the form of information that is not only accessible to people, but also to software agents. It enables data analytics, prediction and indeed optimisation of design and planning alternatives in every control cycle. It is expected to provide project benefits in terms of resource allocation and operation, construction safety, quality and cost and reduce environmental impacts. At a industry sector level, it can encourage standardization of management processes and information, support innovation and leverage economies of scale.

Given the exploratory nature of this research, the conclusions detailed here should be seen as speculative rather than proven. The scope of the analysis was restricted to consideration of the design and construction phase, with emphasis on work performed on-site. As such, much research and development work is needed to progress the DTC paradigm, particularly in the areas of a) interpretation of multiple data streams to deduce status information, b) design of suitable data storage mechanisms, c) potential interactions between project digital twins and the digital twins of construction resources within a project, on the one hand, and digital twins of systems in the surrounding environments, on the other hand, and finally d) applicability of AI tools in this data-centric mode of construction management.

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