BIM, Twin and Between: Conceptual Engineering Approach to Formalize Digital Twins in Construction

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Abstract –

Construction is looking closely as Industry 4.0 paradigm (I4.0) transforms many processes in Manufacturing. Technologies associated with I4.0 were born out of the ever-present necessity of automation (and integration) on the shop floor, as well as of better management in product lifecycle with computer-aided software. Although indeed relevant outside Manufacturing, it is yet not clear how to transpose and apply some I4.0 technologies – for instance, Digital Twins (DTs) – outside the context of a factory or of complex, one-of-a-kind products. Many researchers and software companies from Architecture, Engineering, and Construction (AEC) and Facilities Management (FM) sectors are already working with an ill-defined concept of a DT, and some difficulties had arisen in dissociating it from Building Information Modeling (BIM). Without a direct counterpart outside AEC/FM, the practice of BIM could be likened to Product Lifecycle Management (PLM). Aiming at creating a clearer picture of where, when, and what should be a DT on AEC/FM, through literature review, clustering of common terms found, and a conceptual engineering approach, the present work develops a concept of DT, and layout differences between it and BIM model. It is advocated that DTs should be more about "functional models" for simulations than "product models" for information visualization and organization. As a result, DTs could be used to predict "behavior", and thus enhance and transform management, operations, and maintenance practices. In doing so, there is yet a set of challenges that need to be addressed before one could create and employ properly Digital Twins in Construction.

Keywords –

BIM; Digital Twin; Simulation; Industry 4.0

1 Introduction

Construction is looking closely as Industry 4.0 paradigm (I4.0) transforms processes in Manufacturing, following the digitalization (the use of digital technologies) phenomena which are underway in every aspect of our life in society.

Although indeed relevant outside Manufacturing, technologies associated with I4.0 were born out of the ever-present necessity of automation and integration on the shop floor, as well as of better management in product lifecycle with computer-aided software.

In a way, I4.0 development is an evolution of the quest for a Computer-Integrated Manufacturing (CIM), which Construction had also shared in the past, with its analogous Computer-Integrated Construction (CIC) [1] – a digital representation of the factory or of the manufacturing/construction process to control automated machines, robots, and even cyber-physical systems. Beyond that, there is the operation of the manufactured item / built environment that could be leveraged likewise with I4.0 technologies – although it could only make sense in complex, or automated products or systems.

Regardless its importance, it is yet not clear how to transpose and apply some I4.0 technologies – for instance, Digital Twins (DTs) – outside the original context in which it was first conceived, in factories or for operation of mechatronic systems.

DTs are already being explored by many researchers and software companies from Architecture, Engineering, and Construction (AEC) and Facilities Management (FM) sectors [2]. However, due to an ill-defined concept of DT, some difficulties had arisen in dissociating it from Building Information Modeling (BIM). BIM had been the backbone of all recent advances in digitalization throughout the entire lifecycle of the built environment.

BIM (and Virtual Design and Construction (VDC) [3]) practices have not a direct counterpart in other industries but could be likened to Product Lifecycle Management (PLM) [4][5], as encountered in automotive and aerospace industries, for example. Marketing around the idea of BIM made researchers of other fields, for example from the naval industry [6], to dedicate some attention to its particularities, but in reality, it is not an entirely different technology from

CAD/CAE/CAM or PLM practices.

Aiming at creating a clearer picture of where, when, and what should be a DT for AEC/FM, through literature review, clustering of common terms found, and a conceptual engineering approach, the present work develops a concept of DT, and layout differences between it and BIM models.

Although BIM models could be a framework for all information (geometric, material, and so on) about assets, it is advocated in this paper that Digital Twins, at its core, should be more about "functional models" for simulations [7], which could be used to predict "behavior", and thus enhance and transform management, operations, and maintenance practices.

As one example, a DT composed of a set of models to simulate ageing in infrastructure, and employing historic data collected from structural health monitoring system to fine tune the models, could not only provide a safer approach to preventive maintenance, but also both retro feed information for better and optimized design (data-driven approach) as well as help in wisely management of scarse resources to the most needed infrastructure assets in a city, or country. Would such DT be possible to build and work with our technologies and knowledge?

So, this work aims to demonstrate that BIM and Digital Twin are different practices and are implemented in distinct systems. In this way, a new set of challenges and research questions arises, which need to be addressed before one could create and employ properly Digital Twins in Construction.

2 Understanding BIM

BIM could be viewed as part of a tradition in creating, organizing, and visualizing information inside computer systems about the design, construction, and operation of a product.

That tradition started with CAD (Computer-Aided Design) systems, which were developed to increase productivity and decrease time-to-market in engineering new products [8]. From a software to "draw lines" and produce technical documentations, to feature-based 3D solid modeling, not only drawings but the entire design process was transformed with the use of CAD – and later of CAM (Computer-Aided Manufacturing) and CAE (Computer-Aided Engineering) systems to deal with fabrication, simulation, and its intertwined relationship with design.

At the same time, came the recognition that CAD files, and all engineering knowledge of one enterprise, could be somehow managed by computer systems as well: there was the necessity to create a *framework* to link all data produced.

Figure 1 illustrates the evolution of such systems, from the use and development of CAD Data Management to the PLM of today, for managing all the data related to a product or all products of an enterprise, from initial ideas to design, engineering, manufacturing, operation, maintenance, and disposal.

In the Architecture, Engineering, and Construction (AEC) sector, a similar trend started to be conceived at the end of the 70's: "… the design of a computer system useful for storing and manipulating design information at a detail allowing design, construction, and operational analysis" [9].

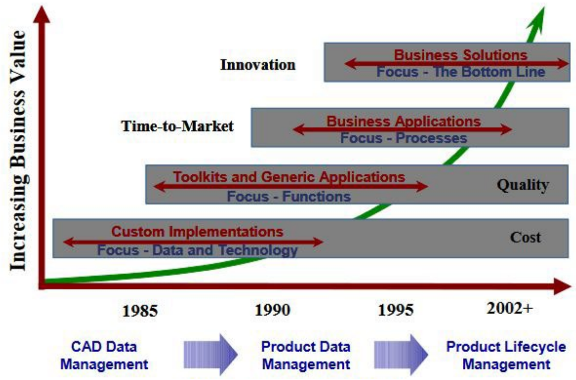

Figure 1. The Evolution of PLM [8]

Without the right technology to put idea into practice at the time [10], it was only years later that BIM authoring software started to appear in the market and being adopted by architects – and it was first likened as the evolution of CAD (Computer-Aided Design) programs. But from the outset, BIM had been conceived as a practice, and its associated software tools, that occurs throughout the lifecycle of the built environment.

Although sometimes BIM was used as acronym of Building Information *Model* [11], opting for *Modeling* emphasizes the *process* of using building information models, as is the case in PLM practices.

Thus, BIM could be viewed as "a socio-technical system that ultimately involves broad process changes in design, construction, and facility management" [4]. The object-oriented nature of BIM 3D modeling, and the highly fragmented platform of software tools for different disciplines in the project of a building, for example, is among the particularities which distinguishes BIM from other similar systems – and the inherent "multi-dimensional nature of the BIM domain" [13].

All the existent workflows with BIM models throughout the lifecycle of the building, potentially bring to attention the problem of interoperability, which now is addressed by the IFC (Industry Foundation Classes) open data schema.

The marketing around such a ‘disruptive’ solution to Construction known problems, leaded people from other segments to consider using BIM, instead of considering PLM for their business [6]. However, BIM and PLM are similar approaches to the same problem [5][4].

As Digital Twins were first thought in the context of PLM [14], there is this potential ill-defined concept of DT which likens it to the BIM model itself. Nowadays, at least two different development paths connect BIM with Digital Twins: Digital Twin of products – operation and Digital Twin of Factories – manufacturing, production.

Firstly, for BIM practitioners, a new trend started to be relevant: how to manage information around old buildings and infrastructure using BIM software tools, if all the design process were done without a digital model.

The use of laser scanning technology – as the service to employ it decreased considerably – and photogrammetry – as the quality of the calculated geometry increased – lead to a trend that many started to call “creating the Digital Twin” or a high fidelity, and digital, model of the built environment. It has been used for facility management, and even Heritage BIM (HBIM) [15].

Secondly, even if 4D BIM models are already used to manage and control production onsite (and there is a natural synergy between BIM, Lean management practices, and I4.0 technologies), the lack of development, and the difficulty in the representation of construction processes (IFC schema has entities representing processes inside the Construction Industry), had been lead to underachievement with regard to the foreseen potential of BIM – in fact, BIM models are mostly Product models [16], lacking a due representation for processes information.

In trying to differentiate DT from BIM, an important fact is that although the idea of a “[…] Digital Twin started off relatively sparse as a CAD description […], in recent years it is becoming *actionable*” [14]. The meaning of the term actionable is given as such: “We can now simulate physical forces on this [CAD] object over time in order to determine its behavior” [14].

BIM models being analogous (although it contains semantic information) to CAD objects, one could argue if the *simulation* should be addressed *inside* the idea of BIM, or if it should be a synergetic action alongside it.

3 The role of Twins in the industry

As already mentioned, the *original idea* behind what now is referred to as the ‘Digital Twin’ was first presented by Dr. Grieves [14] in the context of a PLM course. With the advancement of the digital technologies, researchers started to evaluate the possibility of ‘exchanging atoms for bytes’ [17] – instead of building and relaying in prototypes, decision making in design would be based on computer models and digital simulation.

The *term* Digital Twin appeared for the first time in the context of spaceship development inside NASA with the following meaning: “The digital twin concept is an approach to enable a suite of comprehensive multidisciplinary physics-based models that represent all of the physical materials, processes, and products, and ultimately incorporating these capabilities in the production and operation of spacecraft” [18].

One use for DTs would be to overcome current practices in product development aiming for *performance*. Current practices “[…] are largely based on statistical distributions of material properties, heuristic design philosophies, physical testing and assumed similitude between testing and operational conditions” [19]. Part of that change would be to focus on data-driven approaches, but also on different kind of models, which could be likened to the DTs.

It is important to recapture the necessity of a Twin as first experienced in reality [14]. Few controverse do exist around when the concept of a twin emerged in the industry, and it could be associated with the Apollo 13 Mission. Throughout many different project series to achieve know-how in space travel, NASA developed different physical simulators (15 were in use at the time of the Apollo 13 mission), so it could use them to prepare all team personnel and do diagnostics and test solutions to problems reported from the equipment traveling in space, which are inaccessible to the engineers on Earth. In the advent of problems detected with the flight of Apollo 13, NASA scientists and engineers had to rely on their physical simulators, and on data sent from the real Apollo 13, to test procedures and bring back the astronauts alive. What NASA needed was a solution to predict how systems respond to the environment, to the physics of the real word using computers.

Today, there are also initiatives in building Digital Twins of factories, and its shop floor, where the focus is production optimization, to study different scenarios with new machines, and robots, new shop-floor layouts, without stopping production – and only stop it for a few hours to make changes.

4 Between BIM and Twin

As is happening in the AEC-FM context with BIM, inside the PLM context there are also difficulties in separating and understanding the relationship between PLM and DTs. Among the differences pointed out in [20], Table 1 summarizes the *dynamic* aspects of accessing both systems, considering system-based data structures for DTs.

What could be highlighted from Table 1 is that DTs, differently from PLM system, could be inherently connected to IoT (to receive real-time data) and to Big Data Analytics (for processing), which make it more *dynamic*, with the possibility of working with data streaming.

Table 1. Comparison between PLM and Digital Twins (Adapted from [20])

Criteria	PLM	Digital Twin
Data exchange	Mainly document exchange; Collaborative access to the documents;	Microservices; Via the IoT-platform;
Real-time data usage	Storage; Simulation within the linked models; Hardly possible in document-centered structure;	Machine learning within IoT-platform; Cross-impact analysis within system model; Integration of Big Data algorithms;

Although many elements are expected to be present in a Digital Twin, one should pounder the questions:

- If what constitutes a Digital Twin depends on the existence of a real-time link (data flow) between the real object and its digital representation, it is impossible to have a Digital Twin in the Design and Planning Phase, where there is not yet a real object – in some areas, in these phases it should be called the Digital Thread;
- Timeseries data being important, for what reason it should be used, if not to simulate what is happening with the real object, and to gather knowledge that helps to understand better that specific built environment against theories, knowledge, and experience?;
- What is the use of a high-fidelity 3D model? Just for documentation or traditional management (BIM-HBIM)? In simulation scenarios, would this high-fidelity geometry really be used, or a more abstract model should be used to be computationally tractable? Think of the simplified models for simulating building energy;

All the raised concerns are somehow tied to the idea or ability to simulate a more realistic scenario based on real geometry or real data, or both. Also, it depends on the purpose of the simulation, and in the capacity of a computer to really simulate and predict behavior of the system based on the involved variables.

There is emphasis on the link between the real and the virtual spacecraft, but the data could only be leveraged by means of the existence of models that relates input to behavior. For what purpose one needs "a suite of comprehensive multidisciplinary physics-based models" if not to simulate it on the computer, and predict its behavior in each scenario?

Recently, an increased number of research have been dealing with DTs in Construction. The differences of BIM and Digital Twin were addressed in the literature [21]. But the results of a systematic review of such a theme (a cross-learning between entirely different industries) inside a given community (i.e., AEC-FM) will largely depend on how the first authors interpreted and conceived a framework for, and a definition of, DT to be used in Construction –the conclusions could lead to propagating a biased definition.

4.1 Digital Twin in Construction

The methodology employed in this research consisted in doing a literature review, analysis of the relevant articles which helped in finding not only frequent terms and concepts associated with BIM and Digital Twins and using those concepts to build the concept of a Digital Twin following a Conceptual Engineering approach.

A search in the Scopus database with the combined term **("BIM" OR "Building Information Model*") AND "Digital Twin"** returned 258 results, in February 2022 – the first result from 2017, and some from 2022. Two of the most cited articles provide disparate "visions" over the definition of a Digital Twin for Construction: 1) Focusing on the entire lifecycle of the built environment, authors see the Digital Twin as one evolution of BIM [22]; 2) Focusing on the operation phase, DT are BIM models for predictive behavior based on data from the real asset [23].

Performing a Semantic Analysis in the text of the abstracts of all the 258 results, considering the words found in each text, forming features of one and two words to characterize the topics discussed in each article, and then performing a Clusterization with KMeans, provided one analysis tool to investigate which concepts are commonly associated with DTs, and how they are associated with BIM and its predicted evolution.

Looking into the results of Literature Review, the relationship between BIM and DTs, as seen by the majority of researchers in the AEC-FM field, could be largely divided between two approaches.

As an example of the first proposition [21], BIM models should evolve to become the *de facto* DT for Construction. Between BIM and Digital Twin (a transition or evolution from one to another), there would be 5 steps: 'BIM+Simulation' (considering that most common use of simulation with BIM models), 'BIM+Sensors', 'BIM+AI', and finally Digital Twin. A highlighted point here is the importance of simulation in this approach: without it, there is no DT.

The other proposition recognizes that DTs is a different thing from BIM, but both could be employed together for a different use. One example was presented by [24], with their Digital Twin Construction (DTC) emphasizing the act of building (production on a construction site) with a Digital Twin.

Also, looking into both propositions, one could identify at least two different types of DTs: one for the operation of the asset itself; and other for the production onsite (or even offsite). Both twins could be associated with data from the real twin obtained by a set of sensors.

4.2 Conceptual Engineering Digital Twins for Construction

Following a Conceptual Engineering approach, which “aims to revise rather than describe our concepts” [25], and is a more general approach than Conceptual Analysis, a proposition on understanding DTs for Construction is made.

However biased, let’s consider the role of simulation in the digitization process, and how it enables the integration (it blends more naturally around) of other I4.0 technologies such as Internet of Things (IoT), Cloud and Edge Computing, Big Data Analytics, Artificial Intelligence, and Cyber-physical Systems (CPS).

This consideration. while true to the first application of the terminology or idea of a (digital) twin presented in the literature, it emphasizes the role of simulation, rather than emphasizing the real time link with the real counterpart (which is needed), as the core of the technology – while using it to highlight the challenges in implementation for buildings and construction sites.

In that way, the meaning of the Digital Twin technology was analyzed to elaborate a definition that is useful for the particularities of the Construction sector. During reasoning, it was considered one definition to encompass at least two different applications of Digital Twin for Construction: DTs of the production on the construction site; and DTs of the built environment itself, be it a building or infrastructure.

Figure 2 illustrates the reasoning behind the analysis. In the term ‘Digital Twin’ there is the two terms: ‘Digital’ which means that the DT exists only inside a computer; and ‘Twin’, meaning that there is a real counterpart, and there is a link or relationship between the real and the digital. Following the reasoning, by ‘Digital’, there is the data, or the ‘Representation’ or ‘Model’, and there is a program that uses that data to do something – the use of a Digital Twin. The link or relationship is in fact a ‘Data Flow’ from the real twin to the program that runs based on the ‘Model’ and the ‘Data Flow’.

Delving further the concepts, the ‘Model’ could be a ‘Product Model’, as BIM models could be understood to be [16], and more importantly for this context, the ‘Functional Models’ or ‘Dynamic Models’ – how the current state of model should evolve on the computer with time and data that comes from the real twin. So, with this reasoning, the ‘Program’ is a ‘Simulation’ or a routine to ‘Control’ the real twin based on mathematical representation and a real time data, making a feedback loop.

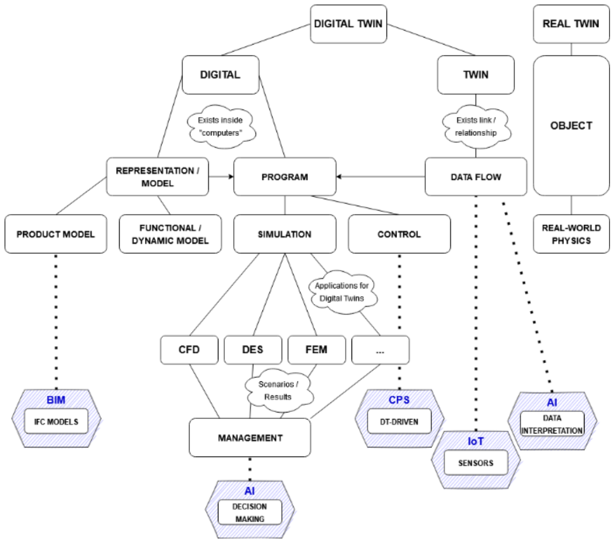

Figure 2. Concept Engineering for Digital Twin in Construction.

In the end, the simulation allows the ‘Management’ and / or ‘control’ of the real twin. So, the Digital Twin should be used to manage or control a real system and is comprised of a product model and at least on functional model that allows the state of the model to change based on external data and a representation of its inner work. In that way, although it is possible to have general functional models, they could be specific based on parameters and real data streaming.

In that definition of a Digital Twin for Construction (Figure 2), it is also illustrated where other technologies associated to the Industry 4.0 concept could be linked with it.

Two points that makes the task to understand the digital twin of the built environment: 1) when one conceives the digital twin of a factory, or the digital twin of a turbine, it is implicit that dynamic models of the robots in the factory and of the manufacturing processes with its transportation and feeding mechanisms, and the mechanical behavior of the turbine do exists; 2) to have sensor information about one thing without having a numerical model in which that data could be used as input, relegates to just data analytics or business intelligence – the only connection possible with the building model is done by human interpretation of the data.

4.2.1 Implications of the proposed concept for DTs

1. The nature of the digital models

As data structure of both PLM and DTs are based on "multiple partial interlinked models" [20], as also is the case in BIM, one import question to be addressed is how to simplify development of DT models, and how to integrate those models in a specific simulation.

If DTs are the combination of functional models and a simulation engine, and the object to be simulated depends on different physical phenomena that works at the same time in the object, one could investigate the state-of-the-art of simulating multi-body, multi-physics, and multiscale simulations in other fields.

As for advanced fabrication methods, there would even concern about multi-dimensional modelling of materials to understand properties of components or parts designed for additive manufacture.

Also, hierarchical models should be considered, as for example, in the case of building simulations which could become part of cities simulations – as the case of DT applied to urban planning and city infrastructure management [26].

One implication of that discussion is that in many applications, the model used to simulate some physical phenomena, it is an abstraction or simplification of the real object – take in consideration the use of bond graphs for simulation [27]. Thus, point cloud-derived BIM models should be less than a desire as the representation for a DT application, being better for visualization and documentation – which are already BIM uses, and not DT uses. Current building simulations use a simplification of the 3D building geometry. Fidelity or High Precision or Accuracy in geometric form are sometimes against limited computation resources in doing simulations.

What need to be clear in deciding the model representation for a DT, is that it is directly associated to its intended use: for example, one thing is a model of the fabrication process – a Digital Twin of the shop floor for prefabricated timber wall panels, or a Digital Twin of onsite operations – and other thing is for the Operation of the Product itself – a Digital Twin of a Building, or Bridge.

2. Applications of DT in the lifecycle of the asset

From all the pioneered works on DTs, it is possible to list three main applications of DTs in Construction:

- The most obvious is to have a DT of a building, facility, or infrastructure for operation, management, and maintenance. The physical representation could be derived from BIM models, or acquired by reality capture techniques, and simulations could be very specific to a given end, such as optimizing operation to save energy, or to predict structural failure, and would involve Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM);
- One of the most important and difficult to implement would be the DT for management and control of production on construction sites, due to the nature of the activities, and the difficulties of tracking people, material, equipment, and building components on site. Also, the nature of the simulations which involves teams of workers, and many dynamic and unpredictable aspects should prove expensive to provide a meaningful result. Probably, simulation would be based on Discrete Event Simulation (DES);
- The most advanced use would be in automated activities in construction, where digital fabrication is possible, and the entire process of automation and control could be based on DT models. In this scenario, a Digital Twin-driven Cyber-Physical Systems could be employed, such as 3d-printing houses;

4.3 Challenges

Despite the lack of consensus around what is a Digital Twin, what few works addressed is what are the differences between new DT and "old" BIM models and practices. Also, what are the challenges in terms of development and implement of DT in Construction? As one could argue, there exists few if any applied DT worth of mentioning.

As is advocated in the previous section, the main difference could be stablished as the simulation core capabilities of DTs, against the management and visualization of information of BIM. Although some kind of simulation is already applied in design phases, simulation in the context of DT have a different nature, and a different proposition.

When one starts to consider simulation possibilities in Construction, what could be highlighted is the large presence of manual labor in production, and of artisanal practices on the field – even if it is more common some industrialized practices for prefabricated houses and apartments all around the world.

Few published articles addressed the questions about simulation of construction processes or simulation on the context of building operation and infrastructure maintenance.

4.3.1 People and Education

The first challenge is who will model, and how DTs will be modelled, if the professionals of the sector are not well versed in that kind of technology? Modeling for simulation, and the know-how to deal with IoT systems and data flow is yet beyond the common knowledge received at academic institutions.

4.3.2 DTs Uses

One reason for that is the main challenge ahead to the way to adopt Digital Twins in Construction: how to simulate something that largely depends on human labor? How to predict the performance of each system that comprises a building, i.e., structure, envelope, etc…

4.3.3 Automatic Onsite Monitoring

Another challenge is how to improve and make widespread onsite monitoring, how to integrate with more predictable manufacturing outputs of prefabricated building components, and how to integrate logistics and the supply chain?

4.3.4 Digital Fabrication and Automated Construction

As the industrialization process becomes the norm in Construction, and the lack of construction works become a reality in more countries, further automated processes, mainly in production, would increase the need of a simulation tool both to test different approaches, as well as to control the process in real time, and to respond to deviations of the plans accordingly.

5 Conclusions

Digital Twins are core components of the Fourth Industrial Revolution based on the digitalization phenomena. It could play an important role on the global efforts to promote productivity and competitiveness in Construction Industry.

Although current practices of BIM could evolve and encompass the functionalities and workflows of the use of a Digital Twin, it seems more naturally and less complex that both work in a synergetic manner towards the end of management.

As core BIM practice is around product models, it will be interesting to enhance the simulations that could be made possible with adding functional models and data acquired from sensors to use it in the operation and maintenance of infrastructure and in Building Management Systems (BMs).

Four challenges were enumerated based on the proposed approach to DTs. These challenges should be addressed so that BIM models of today could work alongside the Digital Twins of the near future.

Future research should address how current simulations related to buildings, infrastructure, and onsite construction could be leveraged to work with enriched BIM models, and with data streams from sensors. Not only better management and maintenance practices could be achieved, but also feedback for optimizing design and planning for new projects.

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