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# Demystifying the Definition of Digital Twin for Built Environment

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**Abstract:** The concept of Digital Twin (DT) has been receiving an increasing amount of attention in the construction management and building engineering research domains. Although the benefits of DT are evident, confusion with regards to the concept of DTs and its relationship with others such as Cyber-Physical Systems (CPS), Building Information Modelling (BIM) and Internet of Things (IoT) remains. This paper aims to help allay this confusion through an in-depth analysis of the definition of DT and its unique characteristics. As such, a review of the past and current definitions of DT and CPS in various domains is performed. An analysis is then conducted to identify the overlaps between the definition of DT with CPS, as well as with BIM and IoT. Finally, given the relatively closer resemblances between DT and CPS, a set of four distinct dimensions enabling their comparative analysis and highlighting their shared and unique characteristics is discussed. This paper contributes to the existing literature by exploring the definition of DT and presenting two original conceptualizations that help further refine the concept of DT in the construction and management and building engineering domain.

**Key words:** Digital Twin, Cyber-Physical Systems, Built Environment, Digitalization, Literature Review.

## 1. INTRODUCTION

The digitalization of the built environment relies on innovative process, technologies and tools to integrate digital capabilities with real-world physical systems. Recent studies have demonstrated that Digital Twins (DTs), Cyber-physical Systems (CPS), and the Internet of Things (IoT) are promising solutions to enable such integrations [1]. In order to fully understand the concepts of DTs and CPS and how they can generate value, various definitions, metrics, and dimensions have been introduced in the literature. While the body of knowledge is growing however, clear distinctions and similarities between the two concepts remain difficult to fully establish. This results in both concepts often being used interchangeably or without distinction. Whereas certain scholars and practitioners consider DT as a reformulation or subset of CPS, others argue that the constituents and characteristics of these concepts are fundamentally different [2]. As a nascent field of research, the lack of clarity around these concepts may lead to confusion in the Architecture, Engineering, and Construction and Facility Management (AEC/FM) sectors, where DT and CPS are increasingly receiving attention.

In theory, the concepts of DT, CPS, BIM, and IoT all enhance the seamless and timely interaction between physical entities and their digital counterparts. However, there is an essential need to compare these concepts and clearly identify their similarities and differences. Both scholars and practitioners can potentially benefit from the results of such comparisons. For example, if these can clarify when DT and CPS can be considered as almost equivalent, then the architectures and tools existing for each concept can be used interchangeably for the future use-cases in the built environment. In light of such potential benefits, this paper sets out to provide an in-depth analysis of the DT definition in the context of construction and building engineering research. The paper first provides a background on the main relevant concepts and their existing definitions in different disciplines. It then compares various aspects of the concepts to clarify their fundamental similarities and differences.

## 2. BACKGROUND

Well before the term “Digital Twin” was coined, NASA implemented a physical twin during the Apollo program in the 1960’s, where a replica of the capsule was created on Earth to simulate and predict the performance of an actual capsule in space [3]. Fast forward 40 years and the original utterance of the term *“Digital Twin”* is credited to Michael Grieves in 2003 at the University of Michigan [4]. Since then, even though the idea of DTs has been around, it took almost a decade to see practical examples of DTs in real-world experiments. Following this trend, scholars and practitioners from various domains started to pay attention to the potential of DTs to connect virtual and physical worlds [5]. For instance, some argue that product lifecycle management (PLM) is a manifestation of DT that was built up within the structure of DT [24]. In the past decade, the idea of digital twinning has attracted increasing attention in the fields of AEC/FM. The application of DTs has shown promising results in allowing industry practitioners to visualize and monitor performance data at different levels of details and granularity across the lifecycle phases of assets [6]. As the benefits of DTs are becoming more evident, the number of scientific publications focused on the digital twinning of the built environment has been surging. However, with all this attention, the concept of DT has become vague and inaccurate due to the way the term “digital twin” has been used in recent publications. Such ambiguities can be explained by the fact that a common definition along with a proper analysis aimed at clarifying the specific attributes and characteristic dimensions of DTs for the built environment, is missing from the literature. Indeed, without a clear definition of DT, researchers and practitioners cannot fully understand the various technical and functional implications of the implementation of DT for the AEC/FM industry. As an example of this plurality of concepts, Table 1 lists some of the existing definitions of the DT that have been widely used in the literature of various disciplines. The current literature shows that CPS can be regarded as a concept with many characteristics and dimensions that are similar to DTs. One of the earliest uses of CPS dates back to 2006, when Helen Gill coined the word CPS at the National Science Foundation (NSF) [7]. Regarding the definition of CPS, the work stated, *“(…) a system with integrated computational and physical capabilities that can interact with humans through many new modalities.”* [8]. Later, Tao et al. [9] defined CPS more broadly, stating, *“CPS are multidimensional and complex systems that integrate the cyber world and the dynamic physical world.”* The latter definition emphasized the integration of computation, communication, and control of physical processes. Both CPS and DTs involve the integration of physical and cyber systems, data transfer in a timely fashion, and correspondence between physical and virtual objects [10], [9]. Conceptually, both consist of three main components: 1) the physical component, 2) the virtual component, and 3) data connection [11]. However, since its emergence, CPS has attracted more attention from academia and industry practitioners than DTs [12]. The disproportionate popularity of CPS over DT in academia is also found in construction management and building engineering research. While the origin of both concepts can be traced back to same period of time, numerous system architectures, use cases, and enablers of CPS have been proposed by academia in the fields of AEC and FM, whereas interest in DTs for the built environment is only recent. Such trends can be explained by the fact that despite their similarities, what is expected from a DT is substantially different from what is expected from a CPS in terms of the system's level of complexity, the rate of data transfer between physical and virtual entities, or the varying range of the system's purposes.

**Table 1.** Most common definitions of DTs

| Ref | Definition | Context | Date |
|---|---|---|---|
| [4] | "The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. Digital Twins are of two types: Digital Twin Prototype (DTP) and Digital Twin Instance (DTI). DTs are operated on in a Digital Twin Environment (DTE)." | Manufacturing | 2017 |
| [13] | "Digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin. Meanwhile, digital twin consists of three parts: physical product, virtual product, and connected data that tie the physical and virtual product." | Aerospace | 2012 |
| [14] | "Digital twin technology is defined as creating a visual and digital model of a physical object. […] it provides a rich virtual representation of the physical environment for the entire life cycle. It can support the planning, tracking, monitoring, operating, risks and problems identifying, improvement, performance optimization, maintenance, and future resources requirement predicting." | AEC | 2020 |

*AEC: Architecture, Engineering, Construction

As the points mentioned above reveal, the research community has been aware of the similarities between the definition of DT and other concepts such as CPS. In response, some research efforts have been recently made to clarify the distinction between DT and other relevant and similar concepts [10]. Moreover, some scholars have proposed multi-dimensional taxonomies to classify and categorize various definitions, relevant terms/concepts, dimensions, and use cases of DTs [22]. However, based on the existing discussions, it is still difficult to quickly gain a profound and clear understanding of the degree to which the different concepts and definitions overlap. In the context of civil engineering, Jiang et al., [10] most recently presented a comparison of DT, BIM and CPS. The authors [10] affirm, *"DT focuses on 'virtual'*, while CPS focuses on 'cyber'." It is not clear what exactly is meant by the words "virtual" and *"cyber"*, or what differences are meant by making such a comparison. In terms of comprehensiveness, the comparisons could be extended by including additional dimensions. With regards to IoT (the Internet of Things), CPS bears considerable similarities with its core concepts. In fact, in light of such similarities, the NIST (National Institute of Standards and Technology) published a document [15] with the purpose of defining the origins of the CPS and IoT terms and their overlapping definitions. Hence, considering the fundamental similarities between DT and CPS, and the substantial similarity between CPS and IoT, the relationship between DT and IoT systems should also be discussed. To fill these gaps, an in-depth discussion on the definition of DT in the context of the built environment is presented in this work.

## 3. MULTI-DIMENSIONAL ANALYSIS OF DT DEFINITION

As previously mentioned, despite their distinct origins, the terms DT and CPS have overlapping definitions, with both concepts gaining popularity among researchers in construction and building engineering research. Moreover, the close correspondence between the concepts of IoT and CPS (as discussed in the previous section) raises questions with regards to the relationships between DT and IoT systems.

To provide an integrated view of the similarities and differences of all these concepts, two visual representations (Figure 1 and 2) are presented in this paper. A detailed description of each illustration follows.

Through a Venn diagram, Figure 1 demonstrates the overlap between the definition of DT and other similar concepts, i.e., CPS, BIM, and IoT. The size of the overlapping areas represents the degree to which each of the two concepts share similarities in their definitions. Moreover, as it can be seen in Figure 1, the concept of DT is categorized into two subclasses, namely, *"practical DT"* and *"ideal DT"*. The key difference between these two sub-classes generally depends on the level of sophistication to which a given DT system has been implemented. In other words, the more complex a DT implementation is, in terms of level of geometrical granularity for example, the closer it is to the subclass of ideal DTs. The reason behind such a classification was to be able to better highlight the range of overlapping definitions. More details on the difference between the ideal and practical DTs are given later in this section.

An immediate observation that can be made by looking at Figure 1 is that the overlapping area between the DT and CPS circles is significantly larger than other overlapping regions. Such relatively larger overlapping area between the CPS and DT is supported by the fact that several similarities can be found when comparing CPS and DTs (see Section 2). A closer look at Figure 1 reveals that among the two subclasses of DT, CPS's definition overlaps, for the most part, with practical DT, leaving a significantly smaller overlap with the ideal DT. Another important observation from the Venn diagram is that despite the large overlapping between the CPS and IoT

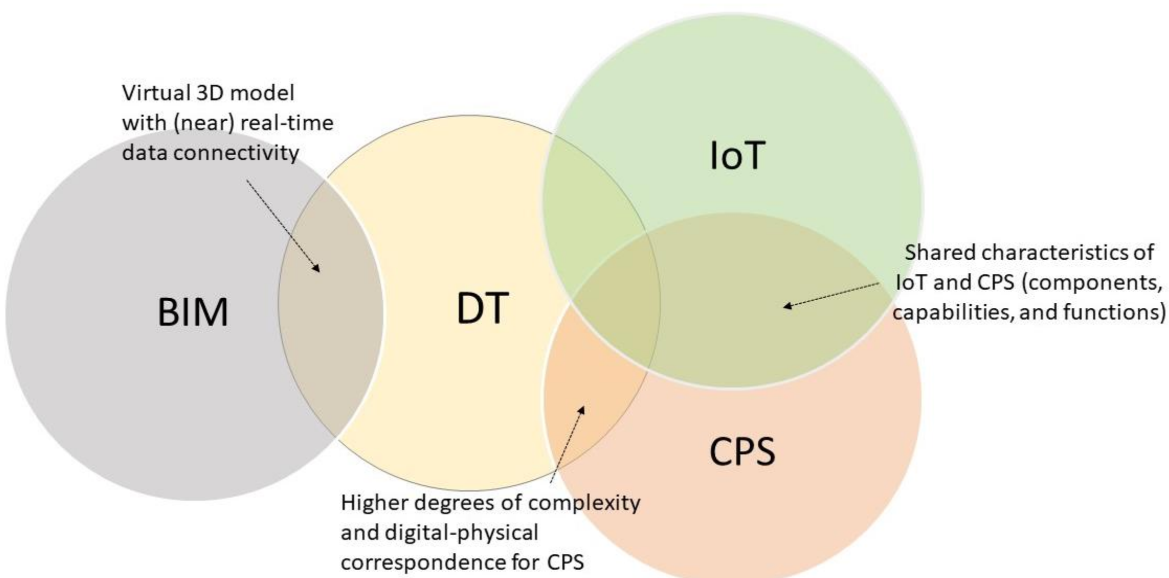


**Figure 1.** Overlapping of the DT definition with similar concepts

definitions (supported by [15]), the IoT's overlapping with DT is small and only touches the practical DT definition. The argument here is that IoT solutions, whether with computation and actuation capabilities or not, can hardly be categorized as digital twinning solutions, as they basically lack the key characteristics of a DT system as discussed below.

Finally, Figure 1 shows that the overlap between DT and BIM is relatively less than with CPS. In other words, compared to BIM, a CPS system has more in common with DTs conceptually, even though significantly higher granular 3D digital representations can be found in a typical BIM model than in CPS-based solutions. Hence, a BIM product can be viewed as a DT artefact as long as the key virtual entities of the 3D digital model yield near-to-definite real-time data connectivity with the corresponding physical entities, and some computation capabilities are in place to serve a set of pre-determined purposes. Given the relatively broad overlapping between the DT and CPS definitions, we conducted a multi-dimensional analysis of their definitions to highlight their similarities and differences more clearly. For this purpose, a set of 4 dimensions were used to perform the comparisons. Among these dimensions, *"Twin Correspondence"* and *"Data Transfer"* were borrowed from [10]. We used *"Visual Fidelity"* and *"Purpose"* as complementary dimensions, as represented in Figure 2.

The results of the comparisons presented in Figure 2 are visualized in the form of spectrums with varying scales for each dimension. The position of each concept was roughly identified on the spectrums based on the key differences discussed earlier in this section. It should be noted that the positions indicted in Figure 2 are not absolute and they are merely meant to provide an intuitive illustration to facilitate the understanding of the main characteristics of DT subclasses (practical

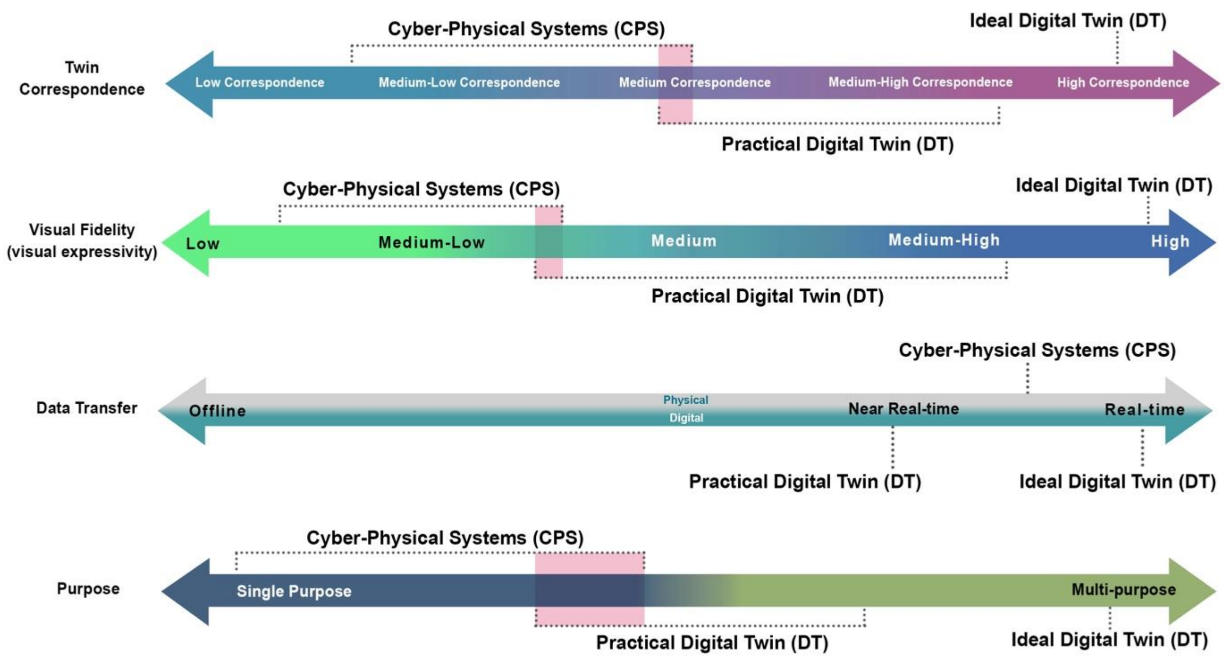


**Figure 2.** Multi-dimensional comparison of DT and CPS systems

and ideal DTs as defined in this paper) and CPS by highlighting their relative similarities and differences from each dimension's perspective.

With regards to the twin correspondence dimension, Figure 2 shows that the correspondence between the physical and virtual components are Low, Medium-Low, Medium, Medium-High and High for CPS, practical DT, and ideal DT, respectively. Such relative positions on the spectrum are in line with the discussions provided in [10] and [12] that state for DTs that each virtual part should correspond to a specific physical one (one-to-one correspondence), while in the case of CPS systems, a given physical part can correspond to a wide range of virtual parts (one-to-many correspondences). The different positions of the CPS and DT subclasses on the twin correspondence spectrum is also supported by the argument that CPS systems mainly rely on computation and less on virtual models, whereas digital models play an essential role in DTs to monitor and predict the behavior of the physical counterparts [16]. An ideal DT should be capable of forecasting and monitoring the performance of an inclusive range of its physical counterparts, thereby requiring a high degree of correspondence between the physical objects/processes and their corresponding virtual twins.

Visual fidelity, which emphasizes the visual expressivity of the virtual representations of the physical components [17] is another critical dimension that determines the differences and similarities between CPS and DT systems. As stated earlier, digital models play an important role in visualizing the structural characteristics of the physical entities in DTs [18]. Ideally, a DT must utilize highly granular representations to be able to support various functionalities such as geometric/spatial analysis, modification of visual characteristics (e.g., resolution, texture, color, etc.) [19]. However, higher levels of visual fidelity most often increase the complexity of the entire system and this could be unnecessarily expensive for practical scenarios [19]. CPS, on the other hand, does not require a highly sophisticated virtual model to process the required communications and computations for the system's purposes. Instead, sensors and actuators are key enablers to integrate physical and virtual components.

Regarding data transfer, both CPS and DT systems allow the data to be transmitted between the physical and virtual components, either in a single direction or through bi-directional communications [20]– [22]. While ideal DTs are expected to transfer the data seamlessly and in real-time, the status of the physical components are most often updated in a near real-time manner in practical implementations of DT for the built environment. For CPS applications, the rate of data transfer varies depending on the system's requirements. For example, while real-time data connectivity is required to monitor safety in a power plant facility, less frequent updates will be satisfactory for the ambient monitoring of a residential building.

Ideally, a DT system would be used for a variety of purposes [6]. This includes identifying and visualizing the past, current, and future states and behaviors of a built asset across its lifecycle stages. Although the ongoing research and development efforts dedicated to novel frameworks and system architectures are pushing DTs towards a multi-purpose paradigm, the majority of the existing DT implementations as well as CPS use-cases are focused on a single or limited number of purposes, mostly to monitor and control physical processes using digital information tools. It can be observed in Figure 2 that except for the data transfer dimension, the other three spectrums of CPS systems are closer to practical DTs than to an ideal one. Hence, the term CPS and DT can be used interchangeably only when the characteristics of the system are close to a less sophisticated solution, i.e., a medium-low twin correspondence and visual fidelity for a certain number of pre-determined purposes.

Based on the discussions presented in this section, DT for built assets can be conceptualized as a multi-purpose, highly granular virtual model, equipped with computing capabilities to reflect the past, current, and future states of an asset's components and systems through rich visual representations; based on the definitions provided in [15]. On the other hand, CPS is a hybrid engineered system that deals with the monitoring and control of the asset's physical states and processes through the use of transducers (sensors and actuators), and cyber entities (e.g., communication and computation software components).

## 4. CONCLUSION

This paper reviewed the past and current definitions of DT and their relationship with other similar concepts, including CPS, BIM and IoT. While these concepts refer to the integration of digital capabilities (e.g., wireless monitoring and real-time analytics) with physical systems through the exchange of data, and computational capabilities, we adopted a broader vision to compare the specific characteristics of each concept from 4 distinct dimensions: twin correspondence, visual fidelity, rate of data transfer, and variety of system purposes. This study presented a multi-dimensional analysis of the DT definition from a theoretical point of view, to facilitate a deeper understanding of what can be expected from DTs in real-world practices. The main contribution of this paper is to further the understanding of each concept particularly for future uses in the built environment.

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