CITY-WIDE DIGITAL TWIN: ARCHITECTURE, ENGINEERING, CONSTRUCTION, AND OPERATIONS AS A 4.0 INDUSTRY

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Cities are expanding not merely in size and intensity but also in complexity and interconnectivity among their components, emphasising the importance of rendering cities smart, which can be achieved through a Digital Twin (DT). Lack of comprehension of what a DT could entail is the focus of this paper. This research paper presents an account of technologies that, when amalgamated, can aid in the development of a City-wide Digital Twin (CDT). A systematic review is included in the study to identify knowledge gaps and create an overall picture of a CDT. Further research and recommendations are also provided to aid in the planning of DTs of existing and prospective cities. Knowledge gaps are recognised and defined after a rigorous literature study. Based on this, a conceptual model is delineated in the form of a schematic of the overall picture, depicting how numerous technologies must be combined to build a CDT where sensing, connectivity, and intelligence are key factors. This study can ignite an innovative debate between diverse stakeholders and professionals from within the Architecture, Engineering, Construction, and Operations (AECO) industry and outside.

Keywords: BIM; digital twin; big data analytics; city information management

INTRODUCTION

The Urban Millennium references the announcement made by the U.N. in 2001 which addressed the problems associated with leaving rural settlements and shifting to cities (United Nations, 2001). The shift to cities and the swelling in population are expected to place extra demands on cities, emphasising the need for more sustainable urban areas which address the challenges associated with the whole life cycle performance at a city-wide scale. The rapid advancement of digital technologies has resulted in significant changes across all industries, leading to a paradigm shift in the way we work, communicate, establish business models, and customise procedures (Hidayatno, *et al.,* 2018). The Fourth Industrial Revolution, also known as "Industry 4.0", is the name given to this technological evolution.

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The industrial revolution refers to the quick and extreme change that has occurred throughout history because of new technology and ways of viewing the world, causing a change in various domains across all industries. Industry 4.0 builds on the technologies of the Third Industrial Revolution, often known as "the digital revolution," and is defined by the fusion, interoperability, integration, and interaction of technologies across physical and digital domains (Schwab, 2016).

The Internet of Things (IoT), Cloud Computing, Artificial Intelligence (AI), Machine Learning, robotics, nanotechnology, and quantum computing are just a few examples of such technologies. Those technologies have transformed all industries, but the effects have been unevenly dispersed (Philbeck and Davis, 2018). Because the rise of the Architecture, Engineering, Construction, and Operations (AECO) industry is a subset of the universal set of gross domestic product value, Industry 4.0 has an impact on the construction industry and built environment as well (Maskuriy *et al.,* 2019).

To be able to deliver a more sustainable product and function under more efficient work processes, the AECO industry must build maps, simplified abstractions of an underlying reality of the present that makes it easier to forecast the future. However, the AECO industry has a reputation for being hesitant to accept new (digital) technologies including BIM and DT (Bello et. al, 2020).

Benefits and problems related to developing a City Digital Twin (CDT) and leveraging the huge amounts of data and information generated by cities are recognised through comprehensive research and literature review. The literature review will begin with an examination of the terms and definitions linked with the implementation and use of technology to manage cities. Second, the study will examine the existing state of maturity in CDT as well as potential future advancements. The literature review concentrated on looking at recent works on the topic of DT in construction that date back no later than 2019 to capture the present state of DT maturity in the industry.

In comparison to BIM, DT is a recent technology notion that is a few steps forward in the digital/virtual world. DT can be as little as a single component of an airplane or a building, or it can be as large as an entire product, a structure, or even a city or an entire country. DT is a trending topic on this scale and is more creatable and manageable than it is on a global scale. However, conceiving, designing, and developing a CDT for a specific city is a lengthy, complex process. At a city-wide scale, DT would cut through a wide range of disciplines, assets, components, and layers of a city that range from physical to non-physical dimensions. While buildings and infrastructure are physical; systems and subsystems of a society's social and economic worldview are nonphysical. A CDT needs to capture and integrate both.

There is a substantial knowledge gap in this regard, not necessarily in the applications of technologies themselves but in stacking and integrating them to deliver a city-wide DT. This knowledge gap, being the hurdle of delivering a DT, has yet to be thoroughly evaluated, analysed, and documented. The aim of this research to produce an account of current technologies which can contribute to a CDT and assess the readiness of the AECO industry to adopt, adapt and amalgamate such technologies. Furthermore, the study identifies knowledge gaps and defines them for more effective communication between the various stakeholders of the industry, including academic researchers and practitioners. This research investigates the interplay of some of Industry 4.0 technologies and how they might help improve existing and future cities.

Technologies and Definitions

Digital Twin

Digital twinning, as well as the technologies that enable and power the DT, has increasingly become an important topic in the (AECO) industry (Mathupriya, et al., 2020). Although the notion of DT is relatively new to the AECO industry, it has long been a part of other industries, such as the automotive industry. The term and concept of DT were first coined by Michael Grieves in 2003 in his lecture on Product Life Cycle Management at the University of Michigan. A DT links the physical system with a virtual equivalent and fully describes actual or potential physical systems at all levels, from the micro atomic level to the macro geometrical level (Grieves and Vickers, 2017). A DT is made up of three parts: a physical system, a virtual system, and the connection that links them together.

The first application of DT was in 2012 by The National Aeronautics and Space Administration (NASA) in which the DT was defined as a multiphysics, multiscale, probabilistic simulation of a high-fidelity as-built physical system that mirrors the state of its corresponding physical twin, in a timely manner, based on historical data and real-time captured sensor data (Glaessge & Stargel, 2012). To realise the anticipated benefits from the DT, which is an ultra-realistic depiction of its physical twin, the DT must consider the physical asset's major interdependent systems and their probable integration scenarios (Glaessge & Stargel, 2012). It can be concluded that DTs are virtual representations of subsystems within a system of systems.

It is critical to distinguish the DT from other notions like digital replica and digital shadows. A digital replica is just a digitised model of a real/physical system with no data exchange between the real/physical and digital systems (Errandonea, et al., 2020). Digital shadows are digitised representations of real/physical systems with a single flow of information exchange between the digital and real/physical systems, where changes in the real/physical system influence change in the digital system (Errandonea, et al., 2020). The DT, on the other hand, has interaction and data and/or information flow in both directions between real/physical and digital systems (Errandonea, et al., 2020). With that being said, the DT still stands at its preliminary stages of application, especially in the AECO industry, as it relies on advancements of various Industry 4.0 technologies, such as IoT, Big Data Analytics, and Machine Learning, to achieve an automated flow of data and information exchange between the physical and digital systems (Deng, et al., 2021).

In the AECO industry, DTs are essential to achieving digital transformation. Multiple DTs will make up a City-wide Digital Twin (CDT), which will represent the city's actual physical components, buildings, infrastructure, and ultimately its non-physical components (Tao, et al., 2019). DTs of physical and non-physical components of a city form the building blocks of a CDT. A comprehensive review of the application of DT in the construction industry was conducted by Opoku *et al.,* (2021) after carefully selecting and searching the literature, in which a total of 22 papers were determined to be related to the research.

The modest number of publications in AECO on the topic of DT may suggest a limited number of studies on DT application in the industry. According to the conclusions of Opoku *et al.,* (2021) research, the industry's focus on DT has increased since 2020; nevertheless, it has mostly focused on a single lifecycle phase of the asset, design, and engineering, while completely ignoring the asset's demolition and recovery phases. Among the 22 reviewed papers, only 8 tackled the use of DT during the operational phase of the asset.

Furthermore, Opoku *et al.,* (2021) research points out that the studies that focused on DT throughout the design and engineering phase were all centred around BIM. This could indicate that the AECO industry is still grappling with the definition of DT, especially as the definition differs by industry and application (Tao, et al., 2019).

Building Information Modelling Management

Building Information Modelling (BIM) is defined as "the use of a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions" (ISO, 2018).

BIM, as the definition implies, is a digital replica of assets authored mostly during the asset's design and engineering phase and can afterward be utilised as a foundation for using other technologies to operate and manage assets and infrastructures. A building information model is made up of geometrical and alphanumerical data with granularity levels that correspond to the asset's function and lifecycle phase (BSI , 2020). An information model of a built asset can be described as a static information model, a digital replica. Examples of city digital replicas are the models of the city of Wellington, Shanghai, Damascus, and Singapore.

Powered by other technologies, an information model of a built asset can be transformed from a simple digital replica to a digital shadow. The implementation of BIM in conjunction with other technologies, including Virtual Reality (VR), Augmented Reality (AR), sensors, IoT, AI, point clouds, and others, has resulted in substantial changes in the AECO industry. Such technologies facilitate Virtual Design and Construction (VDC) in which technology solutions and intelligent algorithms are used to capture and inform design decisions, simulate construction sites, and achieve data-driven project management (Lu *et al.,* 2020). Similar technologies are paired with building information models and used in operations and maintenance, such as remote-sensing devices, cameras, Radio-Frequency Identification Readers (RIFD) and wireless sensor networks.

VDC and technology-driven facility and asset management approaches enable professionals to forecast the performance of a built asset and collect data throughout its lifecycle to support better decision-making. The flow of data and information from the physical asset to the digital asset is created by aligning BIM-based technologies, which is eventually stored in the asset's Common Data Environment (CDE), where it is used to guide decisions that are manually implemented on the physical asset.

Building Information Management, aided by technology, transforms the static information model into a digital shadow, showing a flow of data from the physical asset to the digital asset. Yingtan in China is an example of a digital shadow where IoT is used to capture data within 43 categories (Huawei, 2020).

Given that this does not fully exhibit DT characteristics, which revolve around co-evolving the physical and digital twins in an autonomous process (Zheng *et al.,* 2018), a CDT cannot be realised by simply creating a Common Data Environment that hosts information models of all the city's components and their captured data.

Big Data Analytics

Big Data and Big Data Analytics (BDA) have become the frontier for innovation across all industries in research and development (Chen and Zhang, 2014). BDA is an emerging science that is based on Big Data and AI and has been identified as a critical technology that supports data acquisition, storage, and analytics in related data management systems (Bi & Cochran, 2014). Big Data is an umbrella term for a collection of data sets from a variety of sources that are often too vast and/or complex for typical data processing technologies to manage (Maheshwari, 2017).

Big Data's primary premise is that everything leaves a digital trail that can be captured and used to guide better processes and decisions (Marr, 2015). Big Data has already changed people's lives by making everything smarter: smarter sports, smarter healthcare, smarter homes, smarter businesses, and even "smarter love"! When considering the different layers that make up a city, as well as the areas in which BDA already plays a significant role, it seems Big Data and BDA will become an integral part of the digital infrastructure of future cities. BIM-enabled technologies can capture huge amounts of data from built assets to inform decisions, such as maintenance plans and asset repurposing. Digital Shadows of built assets can use BDA to inform decision-making. However, BDA as a stand-alone technology is insufficient to power a DT

Machine Learning
Machine learning (ML) is an area of AI and Computer Science that focuses on using data and algorithms to mimic the way humans learn and improve accuracy over time. Without being explicitly programmed, ML allows systems to learn and improve from experience. (IBM Cloud Education, 2020).

ML learns from training data and acts like a human for creating predictions by educating itself using Algorithms, whereas BDA pulls raw data and looks for patterns to aid in stronger decision-making. A perfectly built ML Algorithm does not require human intervention. The Scope of ML is to improve the quality of predictive analysis, faster decision making, and support more robust, cognitive analysis.

ML Algorithms can estimate unknown future results, recognising attributes, and enforcing decisions without human intervention. This is known as Deep Learning, and it is a subfield of Machine Learning alongside Artificial Neural Networks (ANNs). ML is more dependent on human intervention, while Deep Learning is not. This is required to satisfy DT characteristics and enable two-way communication between the digital and physical twins. Given the large volumes of structured and unstructured data captured from the city's physical and non-physical layers, which eventually shall sit within a CDT's CDE, all subfields of AI; ML, Deep Learning, and ANNs must be used to fully power the DT's ability to make decisions based on the data captured from its physical counterpart.

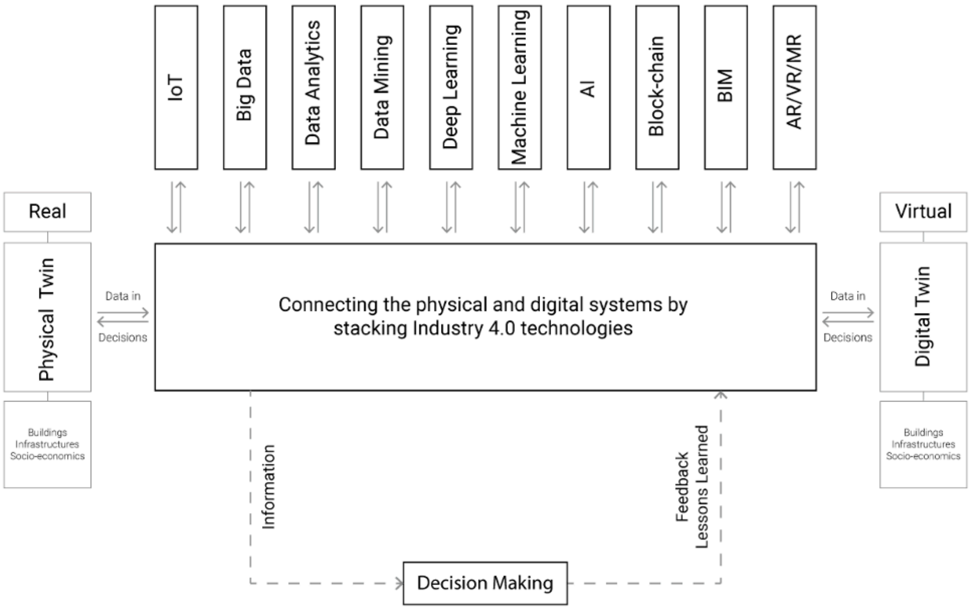
CONCLUSION

A CDT, which consists of an ecosystem of connected DTs, necessitates the usage and integration of a variety of technologies beyond those discussed in this paper, such as security-focused technologies. DTs are virtual representations of subsystems within a system of systems; nevertheless, definitions should not be applied to DTs because their composition is determined by their purpose and use case. To develop and realise the anticipated benefits of a CDT, data and information need to be compatible across all its DTs, implying the necessity of having a uniformed framework. A CDT could provide benefits to society, the economy, business, and the environment. (CDBB, n.d.).

While collaboration is the heart of BIM, technology amalgamation is the heart of the Digital Twin. According to the findings of this research, the AECO industry is aware of current technology that contributes to the construction of a DT, but it is behind in terms of recognising the value of stacking, integrating, and repurposing such technologies. Furthermore, the industry is continuing to focus on the technological connections that can be made while overlooking the social connections, which are more difficult to achieve but are just as crucial in realising a purposeful CDT.

To develop a CDT, a system of connected DTs must be established under a common framework to enable shared data connections between the city's physical and non-physical components. While the AECO industry may not be able to precisely define the DT, a broad grasp of what DTs are and the technologies they include must develop to create DTs that are appropriate for their purpose. Despite efforts to establish city and national DTs, such as the efforts of CDBB and Huawei, semantic interoperability across the ecosystem of connected twins remains unclear and unidentified for the AECO industry.

Figure 1: provides a schematic model of the CDT and the technologies enabling it



By providing a standard industry understanding of DTs, CDT can assist strategic decisions that address the entire built environment, driving positive change for humans, nature, and the planet.

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