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UNDERSTANDING THE CONCEPT OF DIGITAL TWIN IN CONSTRUCTION FROM AN ACADEMIC AND QUEBECKER INDUSTRY PERSPECTIVE

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ABSTRACT: The Digital Twin (DT) concept is increasingly regarded as a revolutionary technological tool for enhancing productivity across various industries. While there is a significant trend exploring its applications in sectors such as manufacturing, automotive and others. In the Architecture, Engineering, and Construction (AEC) industry, its development remains in its early stage, particularly during the design and execution phases. Despite high expectations surrounding its potential, the level of implementation in construction remains low, accompanied by skepticism among some stakeholders regarding its tangible benefits. To explore both the theoretical potential and the practical challenges for DT implementation in construction, this study draws on the analysis of two sources of information. The first source is the scientific literature from which peer-reviewed papers were analyzed to understand the key aspects of the DT concept, including its definition, capabilities, intended purposes, barriers and challenges. The second source consists of semi-structured interviews conducted with a small sample of stakeholders of Quebec's AEC Industry. These interviews aimed to assess stakeholders' knowledge, acceptance, perception and challenges related to DT concept. This study compares the findings from the global literature with a sample of local stakeholders of the Canadian AEC industry. The results of this study indicate a high level of acceptance of DT within Quebec's construction sector. However, they also reveal several factors -most of them related to being in the early stages of adoption- that may help explain the limited implementation of DT in construction projects.

1. INTRODUCTION

In last years, various consultants and software providers have predicted significant growth in the market for technological solutions based on the DT concept. Within the AEC industry, major industry reports have highlighted the potential of DTs to address key factors of the low productivity (ARUP, 2019). More recently, interest from both academics and practitioners has evolved from the conceptualization phase to a nascent stage of practical adoption (Opoku et al., 2021). In in industries such as manufacturing, DT applications have demonstrated the reduction of errors, uncertainties, inefficiencies and expenses as benefits (Singh et al., 2021). A DT can be considered as a technological tool intended for monitoring, controlling, communicating, and acting over physical assets and systems, thanks to the potential to integrate information and communication technologies (ICT), which although have been applied in the industry for many years, they have been used traditionally in isolation, creating information silos and preventing the full exploitation of their potential. However , in construction projects DTs are still in the early stages (Opoku *et al.,* 2021), Several factors contribute to this situation. For instance, the lack of standardization and consensus on the definition and leads to overlaps with other technologies such as Building Information Modelling (BIM), Ciber-Physical Systems (CPS) and simulations (Brilakis et al., 2020; Jiang et al., 2021; Naderi & Shojaei, 2023; Nour El-Din et al., 2022), skepticism about their effectiveness and perception of high risk in their development and application. Additionally, given that various stakeholders believe that DTs can only be applied to physical assets limiting their implementation outside of operation and maintenance (O&M) stages, the integration of the information across the entire lifecycle of the construction projects becomes difficult.

To contribute to the body of knowledge on digital twins and foster discussion about the adoption of DTs in the Canadian construction industry, this study follows a two-stage research methodology to reveal the opportunities and challenges associated with their implementation. The paper is structured as follows: In the second part, a systematic literature review is conducted to extract key insight about DTs from academic sources. In the third part the methodology followed in this study is detailed. In the fourth, the results of semi-structured interviews are presented. The fifth section compares the results of the literature review with those of the conducted interviews. Finally, the last section outlines the conclusions and limitations of the study.

2. LITERATURE REVIEW - DIGITAL TWINS

2.1 Definition

The concept of Digital Twin (DT) was first introduced in 2002 (Grieves et Vickers, 2017). This idea envisioned a manufacturing system represented by two interconnected entities: the one represented by the reality and another a virtual acting as a mirror of the real and containing significant information called its digital twin (Grieves et Vickers, 2017). Regarding its architecture, the initial concept was structured on three components: the real space or physical part (PP), the virtual space or virtual part (VP) and the connections between both. Then, (Tao et al., 2018) argued the need for adding and defining two components, the *"Data"* as the driver of its intelligence, and *"Services"* which define the objective or purpose of a DT application. Concerning its definition, despite its attractiveness and the rapid implementation in industries as manufacturing academic literature shows the lack of consensus and misinterpretation of the definition. For example,- after analyzing several definitions in literature(Semeraro et al., 2021), detected commonalities and focus on these definitions. As a result, they proposed five clusters to help in understanding the concept. A summary of the results is shown in Table 1 where the emphasis, the key abilities and key services structure are presented for each cluster of DT definitions.

Table 1*:* Analysis of DT definitions in manufacturing context. Adapted from (Semeraro et al., 2021)

Nº	Focus	Required key abilities	Provided key services
1	ability to replicate the PP	high-fidelity on information models to represent the real parts	replicate and simulate the states and behaviors along its lifecycle
2	synchronization between PP and VP	bi-directional connection	VP monitoring, coordinating and controlling the PP and vice versa.
3	real-time integration	data Integration from multiple sources and knowledge creation of by analytical algorithms.	insights and improve the performance of the operation of the PP along their lifecycle.
4	behavioral modelling of PP	simulate and emulate behaviors and conditions of the PP	reduction on the uncertainty and complexity of products or systems
5	services	prediction of problems through simulation abilities	mitigation of deviations or damages.

In construction, the lack of unicity in DT definition causes, among other problems, overlaps with related technologies, in particular with BIM (Brilakis et al., 2020; Jiang et al., 2021; Naderi & Shojaei, 2023). Although most of the DT-based solutions in the AEC industry revolve around BIM (Opoku et al., 2021), recent studies recognize additional functionalities of DT over BIM (Nour El-Din et al., 2022)..For (Nour El-Din et al., 2022), the differences between DT and BIM can be clarified in terms of scope, communication and structure. According to (Jiang et al., 2021) these differences can be analyzed by considering aspects such as the existence of a physical counterpart, and the connections and twin relationship between physical and virtual models. For example, although in the built environment BIM can achieve a "standardized semantic representation of objects", DT can extend this towards a more holistic one by adding more complex elements. In addition, BIM has difficulties or is not able to represent sensor network, management and control systems unlikely DT(Nour El-Din et al., 2022). Regarding the communication aspect, since a DT's intent to virtually replicate a physical object, a DT application needs to establish a bi-directional data flow between virtual and physical parts to allow for both parts to be constantly updated, while for BIM this connection does not exist Naderi). Finally, unlike DT, BIM cannot have a continuously uploaded version of the building asset (Opoku et al., 2021), therefore through BIM a twin relationship with the physical part cannot be established (Jiang et al., 2021).

Despite the lack of consensus on the DT definition, some authors noticed that its interpretation has generally been shaped by its application field independently of specific industries field (Opoku et al., 2021; Singh et al., 2021) For instance, a sample of four DT definitions, were identified in the LR (to be presented to the interviewees later in the study), in the context of the AEC industry. Analyzing the definitions we can identify that they are structured around technical characteristics such as real-time data, data exchange, bi-directional communication, virtual representation, computational analysis and modeling. These characteristics proved to be key in the development of the DT concept, but also, to deliver the services are also known as DT abilities or capabilities.

2.2 DT's capabilities or abilities

Precisely, a DT needs specific abilities or technical capabilities to achieve their purposes. A study in the AEC industry conducted by Boje et al. (2020), outlines the significant role of DT abilities to provide "*specific services".* A summary of the identified abilities, differentiated by DT components is shown in Table 2.

Table 2: Identified DT abilities in the context of construction projects (Boje et al., 2020).

Component	Ability	Description of the ability
Physical part (PP) or entity	sensing	To observe the physical world in real-time via the use of sensors
	monitoring	To keep track, inform and issue warnings on relevant physical alterations
	acting	To change/activate/disactivate physical components based on virtual decisions/stimuli
Virtual part (VP) or entity	simulating	To apply engineering simulation models from various application domains
	predicting	To predict the behavior of the physical based on digital simulations and sensing
	optimizing	To apply optimization methods and recommend smart allocation of resources dynamically
	agency	To delegate AI agents capable of managing and actuating the physical based on digital data, following well-defined behaviors, protocols and objectives

In (Boje et al., 2020)study, *"actuation"* is outlined as a key to generate *"reactive or proactive"* changes on the real part of a DT following the orders produced by their virtual counterpart. Although this capability also known as *"automated control of the physical twin,"* is crucial in the ideal definition of a DT (Opoku et al., 2021), it is rare to find it in most of DT implementations (Callcut et al., 2021). Similarly, in the context of civil infrastructures in UK, (Callcut et al., 2021) analyzed results of surveys and interviews related to features and capabilities of DTs. The findings show that five abilities were considered by interviewees as essential in the development of DTs. Table 3 summarizes these capabilities along with the conclusion drawn on the study.

Table 3: Essential abilities for a DT application found in (Callcut et al., 2021) study

DT ability	Key findings
Information query	All the respondents agree that a DT should offer the possibility to be queried to obtain useful information about the physical part (PP).
Automatic control	It is not mandatory for DTs and its absence does not invalidate the concept; besides, it is "quite rare" in DT applications,
Bi-directional connection	Most respondents consider this capability essential for DTs; however, the "data refresh rate" is not obligated to be in real time but rather according to purpose of the application
Intelligence	Most interviewees agree that some sort of intelligence is needed for a system to be considered a DT, otherwise it would be merely an information repository. However, the

	use of technologies such as Artificial Intelligence (AI), Machine Learning (ML), data analytics and model simulations are not indispensable for a DT, they must be implemented only if they align with the purpose.
2D, 3D visualization	Depending on the purpose, the virtual model can represent the PP in either 2D or 3D. However, having a virtual model reflecting reality is not sufficient to qualify as a DT. Therefore, the 2D or 3D model must be complemented by computational analysis tools capable of deriving actionable information.

Another approach to understanding the DT concept is through the differentiation of its capabilities. A widely recognized framework describing DT was proposed by Kritzinger et al., (2018). In their review, they found no universal definition for DT. Instead, the concept was subcategorized into three levels or systems based on the *"level of data integration",* in other words, the degree of automation in the exchange of information between the physical part (PP) and the virtual part (VP). These concepts are the *"Digital Model"*, the *"Digital Shadow"*, and the *"Digital Twin"*. Each of these levels conceptualize changes over the physical and virtual parts as follows. In a "*Digital model"* modification on *the status* of the PP does automatically modify the VP and vice versa". In a "*Dig*ital shadow" "modifications in the PP trigger automatic updates in the VP but not the other way around. Finally in a *"Digital Twin",* any modification in any part VP or PP is automatically and bidirectionally reflected in the other part (Kritzinger et al., 2018).This categorization helps distinguish between applications that aim to replicate real-world object trough a virtual counterpart but vary on the degree of automation in which data is exchanged between the parts.

2.3 DT's maturity levels

An alternative to address the lack of consensus on the DT definition is to adopt a progressive approach . Callcut et al., (2021) advocate for establishing a minimum standard from which a technological application can be considered as a DT, and then, defining progressive levels of complexity to achieve an ideal development of the concept to the highest level. Following a similar perspective, several authors developed the concept on different levels of complexity or maturity. For example, in manufacturing Madni et al., (2019) propose four maturity levels: *"Pre-DT", "DT", "Adaptive DT" and "Intelligent DT".* This classification is based on the sophistication of four key characteristics: model representation, physical part integration, data acquisition and the use of machine learning tools. In the construction field, a maturity model proposed by ARUP, (2019) defines DTs according to four criteria or abilities. The first is *"Autonomy"* referring to the system's capability to perform without human intervention. The second is *"Intelligence"* which reflects the system's capability to emulate cognitive process to perform its tasks. The third, *"Learning",* is the capacity to improve its performance by autonomously learning from the data. The fourth is *"Fidelity"* which measures the degree of accuracy of the measurements and calculation carried out by the DT.

2.4 DT Applications

DT was originally proposed to improve Product Lifecycle Management (PLM) for manufacturing systems by creating a permanent and strong link between the PP and the VP throughout the lifetime of a product or system. However real-world applications are mostly single-purpose or problem driven and single phase driven (Opoku *et al.,* 2021),. For example, in manufacturing, DTs are used in the design phase to support predicting the performance or simulate the behavior of new products or processes. In the production phase, they are used to track the status of a product, process or shopfloor. In operation, DTs are used to control the physical part in real-time. Finally a virtual twin can also pretend to track the status of its physical twin throughout its lifetime (Singh et al., 2021).

In the AEC industry, DTs are mainly implemented in the O&M and construction phases, with fewer applications in the design and demolition or renovation (Akanmu et al., 2021; Jiang et al., 2021). In design some authors and practitioners believe that DTs cannot be applied due to the not presence of a physical object to connect with its virtual twin (Callcut et al., 2021). However, it can be used, for instance, to make decisions in the planning and validation of conceptual and preliminary prototypes through simulations and analysis of what-if scenarios. It can also use data from similar existing or past projects, as well as from the environment of a future project, to provide significant information for its assessment (Jiang et al., 2021).

Like for the design phase, some authors consider that the construction phase- when the physical object is under execution - it’s out of the theoretical scope of DT. However, numerous applications of DT can be supported in this phase, especially construction management functions. (Jiang et al., 2021) found that DTs can effectively help monitor and manage progress, quality and safety aspects during construction. (Boje et al., 2020) found that beyond progress monitoring -where DTs are mainly focused on reality capture-DT can also assist in real-data visualization, safety-support, and enhance the benefits already provided by BIM applications. (Opoku et al., 2021) identified the use of DTs for evaluating structural integrity during construction of critical elements, as well as for managing construction resources such as materials schedules and quality standards. Regarding construction process optimization, some authors propose the joint use of managerial theories with DT applications to create synergies (González et al., 2022; Hamzeh et al., 2021; Sacks et al., 2020). This approach leverages DT capabilities to collect, process, and visualize both geometric and managerial information, enabling synergistic monitoring and control processes. According to Altan & Işık, (2023) such integration offers opportunities to reduce the waste, optimize and innovate in construction process and improve production management. The O&M phase is considered ideal for DT implementation, as physical objects and systems that exist in the real world can be monitored, mirrored, and controlled through digital systems, adhering closely most of DT definitions. Not by chance most of the DT case-studies in the literature are reported during this phase. In O&M, DTs are used to optimize the management of facilities and equipment (Opoku et al., 2021) contributing to the reduction of operational risks (Callcut et al., 2021). Furthermore, the significant investment required for DT implementation is more justifiable during this phase, as there is a longer period for return on investment and greater accumulated experience with its application. As a result, there is increased confidence in the potential for positive outcomes for its implementation.

2.5 Challenges, risks and barriers

According to (Singh et al., 2021), developing a DT application is comparable to build a “*technological mammoth”* which *“comes with its own challenges”* depending of its size and complexity. The most common issues identified in the literature are those linked to the infancy of technology- as the lack of a unique definition, the time and cost of its implementation, the lack of technological standards and regulations for its development and implementation. as well as the shortage of technical expertise in the AEC industry, and the well-known issue of interoperability(Akanmu et al., 2021). Concerning the risks, the novelty of this technology and the low level of implementation in construction projects generates insecurities and a medium to high perception of risk on some stakeholders. Participants in the (Altan & Işık, 2023) study, perceived as key risk factors to develop a DT solution the ”choosing the appropriate technologies”, “the dependency on skilled people and training”, interoperability issues, integration and data issues. Additionally, as factors to explain high cost of DT solutions, the need for highly skilled workforce, the high sophistication of DT systems and components, the data collection and processing technologies, along with the maintenance and energy requirements. All these factors can obstacle the full exploitation of the concept in the construction industry.

3. METHODOLOGY

To develop this study a two-step qualitative approach was adopted, combining a literature review with semi-structured interviews. In the first stage, an exploratory literature review was conducted using Scopus and Web of Science databases, supplemented by both backward and forward snowballing techniques. This process involved identifying, reading, and analyzing in depth high-impact papers related to the definitions, capabilities, purposes, applications, challenges, risks and barriers of digital twins -both in general and with specific emphasis on their status in the AEC Industry. The second stage involved conducting a series of semi-structured interviews. This step followed a preliminary survey designed to identify industry stakeholders with prior knowledge of BIM or DTs. Invitations were sent to members of a public group of practitioners interested in innovative construction practices, as well as to an academic research group in construction, both located in the province of Quebec, Canada. As a result, six individuals were interviewed in either French or English. The findings from the literature review served as theoretical foundation for developing the interview questions. This questionary included thirteen questions organized into three sections: two with open-ended questions, and one with closed-ended questions using a Likert scale to assess the degree of agreement or disagreement with specific statements.

4. RESULTS – FINDINGS OF THE INTERVIEWS

This section presents the key findings of the results obtained from the interview conducted in this study. References to specific interviewees are made using their assigned identification letter, either through direct citation or using brackets, for example (B): refers to interviewee B.

4.1 Results concerning open-ended questions

Regarding the relationship between BIM and DT, all respondents agree that both concepts are closely linked. In the context of the AEC industry, they consider BIM to be the backbone of a DT application for most cases. Interviewee B stated that *“from the beginning of the project, it is necessary not only to determine whether the built asset will require a DT in its O&M phase, but also whether the BIM model will be used to visualize and store the related information. In such cases, the data structure used during the design stagemust take into account the requirements of the data structure needed for the future DT application”.* (B) also mentioned the ongoing confusion in the industry regarding the distinction between BIM and DT. Although both technologies are related, they are not the same” (C, E). One important distinction is that BIM is a static system, while DTs incorporate real-time data collection and processing (C). Moreover, DTs can be developed using other enabling technologies such as Internet of Things (IoT) (E). When it comes to defining DTs, responses varied. Interviewee C referred to defining a DT as a “complex task” (C). For half of the respondents, a DT represents a physical object, such as a building or one of its components. For the other half, a DT may also represent a system that does not yet exist in the real world, such as a construction process. Despite these differing perspectives, all interviewees agreed that a DT is useful to integrate both geometric data (e.g., 2D, 3D models) and non-geometric data (e.g., plans, specifications, technical information, warranties, as built models, and more). (B, F), emphasized that real-time data capabilities are essential for a DT. (B) emphasized the importance of using sensors and captors to manage specific aspects of physical assets, such as energy consumption. (D) highlighted that a DT is not merely a 3D model; it must enable bidirectional communication between its virtual and physical components. Interviewees B, D, E, and F pointed to the relevance of DTs during the O&M phase. For (F) a DT “must be the mirror or the project as it was built and it performs”, and ideally it should also reflect *“all the changes that occurred during its construction and operational phases.”*

Related to the capabilities of DT r, Interviewee (A) and (D) emphasized that DT must provide accurate technical and dimensional information about the building. For (B), a DT should reflect the real-time status of the physical asset and support its modification. For (C) it also must enable the integration of various modules to generate useful information. To this purpose, the ability to process data in real-time was identified as essential. Other important capabilities include the prediction of building-related issues through simulation and visual management tools. (D) added that DT should enable remote interaction with the building and allow for real-time diagnostics of systems operations, as for example temperature and humidity levels. For (F) beyond facilitating building management during the O&M phase, DTs can also offer valuable insights into the structural health and lifespan of a building along with the documentation of *“historical and patrimonial information,”* which can be beneficial not only for current owners but also for future stakeholders. Regarding the role of DTs during the design phase, most interviewees expressed skepticism about its applicability since the real-world object does not yet exist Furthermore, B, C, D, and F did not support the idea that DT abilities as simulation could be effectively used to improve the systems’ design. In contrast, interviewee E, stated that one of the most valuable benefits of DTs in this stage is to support decision-making for future improvements, based on current performance data or historical data generated by the DT. Finally, although interviewee F admitted *“don’t see a clear utility for DTs”*, at this stage they acknowledged that it could serve to *“begin collecting the required information”* for the DT’s defined purpose in the O&M phase, even if that information may evolve over time.

Reponses regarding the role of DTs during the construction phase were quite aligned with those provided for the design one. A majority of participants agree that the DT concept cannot be fully applied during this phase, citing similar reasons as for design (B, C, D, F). From another perspective, while a BIM model containing geometric and technical information may be useful for conducting constructability analyses during pre-construction, it does not qualify as a DT (B, E). In cases where a DT application with the ability to collect and process construction-related information is developed, *"its usefulness could be appreciated from the general contractor's perspective"* and not for the final client-unless both parties are the same, as may occur under some contractual arrangements. For C, beyond reality capture functions, DTs could be used to monitor the performance of workers and equipment, generating insights that could be used to improve similar future construction projects. For (E), a DT application could be developed to monitor temporary construction installations or facilities, aiming to enhance understanding of these systems and support improvements for future projects. Similarly, to their role in design, for (F), DTs can also begin to gather relevant data during construction-this time reflecting a status closer to the as-built conditions. About their use for construction management, most interviewees reiterated that the concept is more suitable for O&M purposes instead of construction management. However, toward the end of the construction phase, an updated BIM model with an enriched technical database of the as-built status can assist the operation team not only enabling the early detection of potential issues (A, B), but also allow for the prediction of future deviations using simulation tools before the building's commissioning (B). A DT could be focused on enhancing site and workers safety, track materials and personnel, and assessing performance (E). Applications able to capture images and video of construction processes could also serve as forensic documentation in the case of future claims or disputes. Finally, a DT can facilitate timely comparisons between planned and actual progress (F). The latter would not only support the early detection of deviations but also inform better management practices for future interventions (F). Assessing the level of acceptance of DTs, all participants from the Quebec stakeholder sample agreed that the concept holds strong potential to improve the industry, especially in the O&M phase. As to direct beneficiaries, DTs are seen as especially valuable for built asset owners, as well as for building management and O&M teams (F). Among interviewees from academic backgrounds (A, C), the DT concept generates high expectations and appears to be well accepted although its practical implementation remains limited to date. According to (B) DT's implementations are at the starting point. According to (F) DT has not only the potential to extend the lifespan of buildings and infrastructure, but also to enhance asset value in the case of resale.

With regard to barriers, there is no consensus on this topic. One major obstacle cited is the financial aspect, particularly the significant investment required for developing and deploying DT applications (C, F). (B) and (D) emphasized the need for increasing maturity on BIM implementation, as a previous stage to DT adoption. Besides, traditional construction methods and static mindsets can help hinder DT implementation (A, E). For (A), adopting DTs is *"quite more difficult,"* especially because many construction practices have yet to integrate BIM technologies. Interviewee E considers the "culture of immediacy" as an important factor to the adoption of innovative long-term solutions. Furthermore, the lack of "standardized" methodologies and technologies to develop DTs creates uncertainty around expected outcomes and return on investments (B). Even if financial investment were not an issue, the O&M managers must be fully convinced and ready to implement the DT solution-what can be similar in some cases, to develop a new product from zero (B).

Regarding risks, interviewees generally identified three main types: technical, operational, and financial. However, most respondents emphasized the relevance of technological ones, for instance, interviewee D pointed out interoperability as a key concern, noting the difficulty of integrating diverse software, hardware, and communication protocols within the unified environment that DT requires. For (A, C, F) a significant risk lies in the possibility of obtaining inaccurate information generated by the DT due to technical failures, such as malfunctioning sensors, connections and processing methods used to generate the information. As an example, if a DT relies on AI to interpretate data, insufficient or inappropriate training of the model could result in wrong interpretations of the reality (F). Additionally, to support the operation of a physical asset over a long period, a DT must be adequately maintained and updated throughout the entire O&M phase (F). A malfunction of DT can also generate operational risks. For example, inaccurate information provided by the DT can lead to real-world malfunctions, which can be particularly critical in systems where bidirectional connections are established between virtual and physical assets (C). Financial risk can arise if the abovementioned risks materialize (B, E, F), which can potentially lead to a financial failure for projects whose operation relies on DTs (E). Finally, concerning challenges, most of them involve DT solutions developers and suppliers. On the one hand, better support from technology suppliers can help balance technical requirements, cost and functionality (B). (C) highlights as a major technical challenge the establishment of a "real bi-directional" connection between physical and virtual components. On the other hand, addressing interoperability issues and developing more affordable and user-focused DT solutions are also relevant claims (D, E). However, actions from the AEC industry are equally necessary to promote DT adoption. For instance, the industry could support the dissemination of successful DT use-cases and the creation of practitioner and developer's taskforces to share experiences covering not only general insights but also tangible results, mistakes, challenges, and best practices in implementation (F).

4.2 Results concerning closed-ended questions

This section of the paper presents the results from the close-end questions part of the interview Concerning DT's capabilities, all interviewees disagree that a DT should imperatively visualize the physical part in 3D; half of them agree that the reality can be represented indistinctively in a2d or 3d model, depending on the purpose of the application. Regarding the dilemma about what a DT can represent, most interviewees disagree that a DT must replicate only physical or tangible assets. In fact, the vast majority share the view that a DT can also be used for intangible entities such as, systems or processes in the real-world, in addition to components or entire elements. Concerning real-time communication capabilities, most interviewees agree that the link between the physical and virtual parts should occur instantaneously (real-time) and automatically (with minimal human intervention). In alignment with this, most respondents did not support the idea that communication could merely in "right time" (i.e., when the information is required but not necessarily automatically), even if the flow of data between the physical and virtual parts is automatic. Regarding DT's ability to interact directly with the physical part via bi-directional communication, opinions are quite divided between those who believe this is not mandatory, and those who consider mutual interaction as key for DTs. Concerning the purposes of DTs, all the participants view the generation of insights about the physical part as a key role for DTs-by providing significant information about its health, status, behaviors, performance and more. Finally, as to the intelligence as a key DT attribute, half of respondents consider the incorporation of some form of intelligence (like AI, machine learning, simulations, predictions, data analytics, etc.) as mandatory.

5. DISCUSSION

This study aimed to compare findings from the literature on the DT concept with the perspective of Quebec's construction stakeholders, in order to provide a local overview of the level of knowledge and acceptance and potential barriers to its implementation. Although invitations to participate were extended to a wide range of construction practitioners, the limited number of interviewees significatively restricts the generalizability of the findings.

Findings from this study show that during the initial stage of DT adoption in the AEC industry, the concept was confounded with BIM by both academics and stakeholders. Although clear distinctions have been identified in the literature. Findings show that that some stakeholders of Quebec's stakeholders see BIM models-enriched with building information- as a synonymous with DT applications. This confusion is particularly noticeable in relation to DT applications during the design and construction phases. According to the study results this may be explained, on the one hand, by the strong connection between both concepts in the construction context, since BIM is considered the backbone of DT applications, and, in the other hand, by the lack of a clearly defined role for DT during these phases. Regarding the DT definition, although the original idea conceptualized virtual twins as replicas of their physical counterparts, supporters of the concept have adapted the definition across multiple fields and specific purposes, leading to a multiplicity of interpretations. According to Opoku et al., (2021), this ambiguity makes DT implementation more challenging. The definitions found in the reviewed literature agree that DT can represent not only physical objects but also intangible entities, such as systems and processes. This aligns with the interview findings supporting the idea that DT has a potential to aid design and construction activities, however, the specific roles and purposes of DT in these phases—particularly its distinction from BIM —remain unclear. The conceptualization of DT also revolves around to identifying its "essential" capabilities. Definitions in literature consistently highlight capabilities such as computational analysis and intelligence, real-time capture and processing, and bi-directional connections with automatic data exchange between physical and virtual parts, which are also reflected in the interviewees' responses

Academic literature and interview results converge in highlighting the need for a unified definition of DT. As noted by interviewee (B), the lack of consistent definition and standardized development framework increases the perception of risk and undermines confidence in DT's potential to deliver positive outcomes. While most stakeholders agree on the importance of reaching a single universal definition, this might be unrealistic due to the wide range of DT applications and system architectures that aim to replicate real-world entities. In line with (Callcut et al., 2021), the authors of this study advocate for the development of domain-specific definitions.. Additionally, for each field of application, defining DT in terms of maturity models or levels- where DT capabilities are progressively depicted- as proposed by (ARUP, 2019; Kritzinger et al., 2018; Madni et al., 2019) — could help structure DT solutions in a way that requires reasonable investment levels and yields tangible short-term results. This could serve as an incentive to accelerate DT adoption in the AEC Industry.

Future research can build upon the findings of this study either by exploring the root causes that hinder DT adoption in construction projects or by developing and testing practical use-cases to foster its implementation-especially in the design and construction phases. As an additional weakness, this study did not explore other contributing factors to the low implementation of DTs that have been identified in prior research such as challenges related to data management, including security, privacy, and governance.

6. CONCLUSIONS

Nuanced by the key limitation of this study-namely the small sample of interviewees-the results indicate an intermediate level of knowledge and a high level of acceptance for DTs within Quebec's construction environment. However, insights especially from interviewees reveal the existence of potential barriers or reasons behind the low level of DT implementation in construction projects. One notable example is the widespread belief that DTs are only applicable during the O&M phase, due to the need for the existence of physical assets or buildings. This assumption limits recognition of the potential benefits that DTs could offer to other construction project phases such as design and construction.

From technological perspective, the respondents' perception that a DT application must involve only high-tech systems capable of continuous monitoring and control reinforces the misconception that there is only one type of DT-an overly complex and costly system comparable to a "technological mammoth". This notion, coupled with the lack of standardization in DT architecture and outcomes, increases the perception of risk associated with DT adoption.

To contribute to a better understanding of DTs, this study proposes the following conceptual approach to DTs in the AEC industry: *"A DT involves the development of a virtual system with technical capabilities that allow it to mirror, monitor or control real-world entities-such as components, assets or systems-throughout part or all of their lifecycle. It integrates Industry 4.0 technologies responsible for collecting, processing, and visualizing information tailored to it specific purpose. In the AEC industry, a DT application can support various services across different phases of a construction project. While it often relies on BIM as its information model, it is distinguished by its ability to capture and process data in the right-time and at varying levels of autonomy depending on its sophistication or maturity. "*

Finally, the study highlights the urgent need for increased collaboration between academia, AEC industry stakeholders, and DT developers and suppliers to build a shared vision of how DT applications can enhance construction projects across all phases-including design and construction-and to identify and address the barriers hindering its implementation, as a meaningful contribution to improving productivity within the construction industry.

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