An Extensible, Service Oriented Digital Twinning Framework to Enable Implementation Planning and Capability Development in the Built Asset Industry

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Abstract
Building Information Modeling (BIM has been hailed as a revolutionary, yet foundational concept supporting the digitalization of the built asset industry, acting as a centralized service-based platform supporting the planning, delivery, and use of built assets. The advent of the Internet of Things and connected objects, allowing real-time coupling of digital and physical worlds, has prompted the concept of BIM to evolve towards that of Digital Twins (DT). Being a nascent concept, questions still abound around DTs, their application, operationalization, and most importantly their benefits. This paper presents findings of a research program that aimed at better defining the application of digital twins in the built asset industry, their adoption and implementation and the capacities needed to support this. The results include the development of a service-oriented DT framework, which is validated through an action-design research project with a large real estate company, on the implementation of a DT of a large commercial complex.

Keywords: Digital Twins, BIM, Capability development, Adoption and implementation, Digitalization, Asset and operations management, Built asset industry

1 Introduction

The concepts underlying Digital Twins (DT) are slowly being formalized for development and application within the built asset industry. Within the last decade, researchers have sought to define, develop, implement and validate these building blocks to better frame Digital twins, and their brethren, cyber-physical systems (Davari et al., 2022). For the built asset industry, digital twins can be situated in an accelerating transition towards built asset data and information in digital form, mainly predicated upon the advent of Building Information Modelling (BIM). Therefore, whereas BIM is the collaborative process guiding the development, management, maintenance and use of a built asset's information model (Gouvernement du Québec, 2021), DTs add the notion of real time, bi-directional interplay between digital and physical worlds (Khajavi et al., 2019). Both concepts are centered around effective decision-making, be it manual, automated, or autonomous, across built-asset lifecycles (Jones et al., 2020) and are predicated on the flow of high-quality, reliable and accessible data (Caramia et al., 2021). BIM, however, has matured as a concept over the last decades, since its inception in the 1970's (Eastman, 1975), especially since the early 2000's when government bodies have begun to mandate its use on publicly funded projects (Jiang et al., 2021) and since major software vendors commercialized tools and platforms to enable its everyday use . DTs, on the other hand, remain a nascent concept with many of its constructs, and their instantiation, being experimental and untested. In parallel, and not unlike what happened with BIM, the evolution of DTs appears to be led by industry and practitioners. This potentially leads to issues that were observed with BIM adoption being driven and focusing solely on the technical aspects of its deployment (the devices, the integration, the modeling, etc.), with the process, policy and human aspects being put to the sideline. While there has been a considerable amount of research put into the development of BIM adoption and implementation frameworks, identifying key constructs, their relationships and how they influence the deployment of BIM at the industrial, organizational or project level, the same can't be said for the adoption and implementation of DTs. At this point the question of whether there is a need for distinct adoption and implementation frameworks for BIM and DTs is legitimate but is beyond the scope of this paper. Rather, work is needed to continue exploring the relationships between the concepts, how what has been learned from the past two decades of BIM adoption and implementation can be transferred or adapted to the context of DTs and more importantly how this can help accelerate the propagation of DTs within the built asset industry. On the other hand, there is a need to understand the commonalities and the distinctions between both concepts and how these inform their adoption and implementation.

The research presented in this paper aimed to assist and enable a large built asset owner to plan and implement a DT of one of their flagship assets. To achieve this aim, an extensible, service oriented digital twinning framework was developed and piloted to enable implementation planning and capability development within the partner organization. The framework was developed, piloted and validated over an 18-month period through an action-design research project, whereby a member of the research team was embedded within the partner organization's innovation department as well as its asset management department. The research project included a diagnostic phase as well as action planning and taking phases, in which the framework was developed and tested. The framework itself was used to better target the business processes to digitalize through digital twinning and was mainly focused on the partner's facility and asset management processes.

2 Background

DTs have been defined as " integrated multi-physics, multi-scale, probabilistic simulation[s] of a complex product [which] uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin." (Tao et al., 2018) DTs in the built environment have been specifically defined as : "a dynamic digital replica of physical assets, processes and systems through involving internet of things (IoT) devices and information feedback from citizens" (multiple authors in Lu et al.(2020)). DTs exist on an end of a continuum of data and information flow and integration as shown in figure 1.

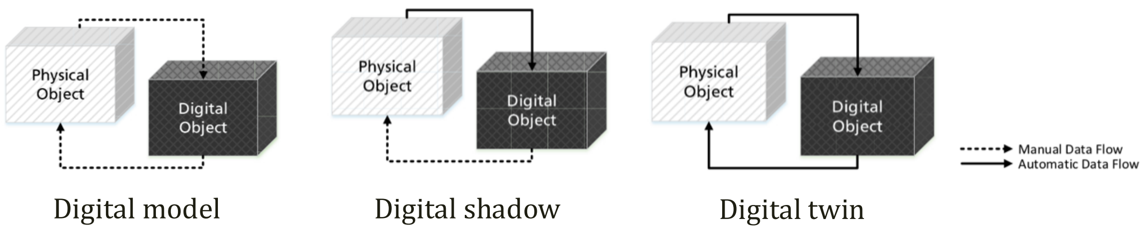

Figure 1 Types of data flow and levels of data integration (source: Kritzinger et al. 2018)

The components of DT, and the domain it constitutes, have been emerging over the past few years. For instance, Davari and Poirier (2024) have developed a taxonomy of built asset information coupling that is articulated across two levels. The first level introduces dimensions of built asset information coupling which includes: Information Couples, Coupling States, Coupling Impacts, Coupling Purposes, Coupling Outcomes, Coupling Actions, and Coupling Enablers. The second level develops coupling metrics. These components serve to frame the development of knowledge across the DT domain.

A growing body of research work has investigated the specific uses of DTs (e.g. services) and their underlying architectures and requirements. Within the built asset industry, specific use cases covering all aspects of the built asset lifecycle have been developed, be it during the design phase, the construction and the asset management phase (eg. Zhang et al., 2023). Regarding the latter, DTs support the transition from reactive and preventative towards predictive and ultimately prescriptive asset management (Hosamo et al., 2022). They also open up a number of opportunities as they relate to the core business functions of built asset owners and operators across multiple domains, including transport infrastructure, healthcare, education, commercial, etc. These use cases include everything from energy management (Arowoiya et al., 2024) to maintenance management (Villa et al., 2021) to occupant wellbeing (Shahinmoghadam et al., 2021)

Lastly, DT, as it falls into the context of digital transformation, is subject to similar adoption and implementation dynamics as have been found in related fields, such as BIM adoption. However, it does imply a different level of digitalization than BIM due to the data capture, transmission and integration that needs to happen to enable DTs (Davari et al., 2022). These tend to involve different business units than are called upon in the BIM adoption and implementation process, such as building operations and control teams. Moreover, DTs require a two-pronged approach, namely due to the modeling requirements as well as the data capture and integration requirements. While past work has investigated BIM adoption and implementation for owner organizations (Chowdhury et al., 2024) the advent of DTs adds an extra layer of complexity in the digitalization process. They also can add considerable cost due to the hardware requirements as well as the storage and processing requirements. Questions around deployment strategies and return-on-investment, while still relevant for BIM, are now exacerbated by the emergence of DTs. The research presented in this paper investigates these emerging dynamics from the lens of large built asset owners.

3 Methodology

The main objective of the research project was to assist and enable the research partner's organization, a large real estate company based in Montreal, Quebec, Canada, that owns over 1 200 built assets in the residential, commercial, and industrial sectors, valued at over 70 billion CAD, to develop a digital transformation plan predicated upon the deployment of BIM and DT. An 18-month action-design research project was undertaken, where a member of the research team was embedded within the organization. The research project was focused on one of the partner organization's flagship properties, a +/- 386 820 m2 commercial campus located in downtown Montreal, composed of five office towers, a commercial gallery and a 900-place underground parking.

An action-design research cycle, as described by Sein et al. (2011), was followed. The organization first underwent a diagnostic phase to understand its current situation and define the problem state. To do so, all relevant individuals were met and interviewed to identify expectations and needs as it relates to the management of the campus. Relevant artefacts were also consulted and analyzed, including strategic plans, asset management plans, organizational information systems (ERPs, BMS, CMMS, etc.) and others as deemed necessary. The action planning stage served to define the organization's objectives and lay out its digital transformation plan. To support the action planning stage, the digital twinning framework presented in this paper was built, due to the lack of existing investigative and planning tools to undertake such an exercise. The objective of the framework was to help in the identification, evaluation and planning of the DT services (or uses) to be implemented. The action taking stage consisted in the piloting of a DT implementation on a specific sector of one of the buildings on the commercial campus, which allowed the intervention and evaluation of the proposed artefact. Findings were validated through close collaboration with the organization's director of innovation and sustainability as well as the director of facility management. A final presentation of the work was made to the organization's upper management.

4 Results

The framework developed in the context of the research project served to guide the identification and prioritization of specific DT services (or use cases). It is articulated across two axes as shown in figure 2.

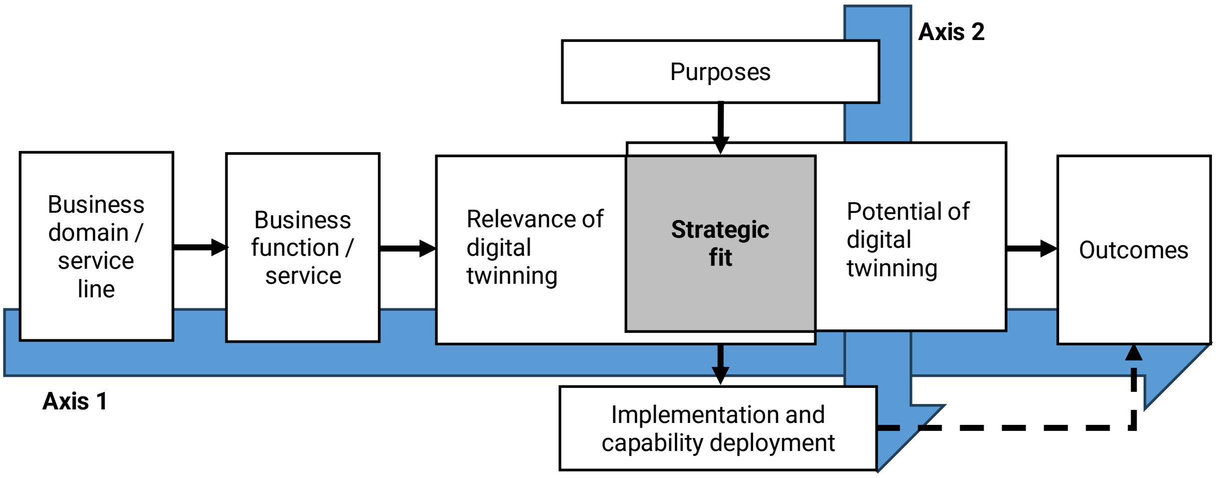

Figure 2. An Extensible, Service Oriented Digital Twinning Framework

The first axis are the *business domains* (service lines) and *business functions* (services) that can potentially benefit from being digitalized through the digital twinning process. In this case, the focus was put on the partner organization's business domains and on the services rendered in the context of its AM/FM activities. The following business domains were considered in the analysis across which 120 services were defined. These services were identified through discussion with the partner organization as well as an extensive literature review.

- Safety & security
- Real estate & property
- Capital projects
- Facilities & assets
- Operations & maintenance
- Environment & Sustainability
- Mobility & transportation
- Human experience, health, wellness & services
- Knowledge & innovation
- Contracting & procurement
- Finance
- Community & Stakeholder Engagement
- Human resources

The second axis are the purpose or the expected outcome categories guiding the digital twinning process. In this case, the digital twinning (or coupling) purposes, as described in the *Built Asset Lifecycle Information Coupling Taxonomy* by Davari and Poirier (2024), were used. These include: Planning (e.g. the process of setting goals, determining the actions required to achieve those goals, and outlining the necessary steps and resource); Monitoring (e.g. the process of systematically tracking and evaluating the progress of a project or activity against defined objectives or standards over time); Simulation (e.g. the use of a model to recreate and study the behavior of a system or process in a controlled environment); and Automation (e.g. performing a task or process with minimal human intervention).

The core of the framework articulates two perspectives which serve to inform the digital twinning process: the potential of information modeling and integration (or digital twinning) to support a specific service and the strategic fit between the DT purpose and the service. The *potential of digital twinning* is not binary as it relates both to the intensity of information modeling and integration and the dynamisms of its sources. This, in turn, relates to both the concept of "levels of BIM", e.g. Level 0 through 3, level 2 now being replaced with BIM according to ISO 19650 per the UK BIM Framework (UK BIM Alliance, 2021), and the Coupling Level (CLevel) in Davari and Poirier (2024) or the level of integration in Kritzinger et al. (2018). Indeed, combining both approaches and placing the level to which information is modeled, exchanged and/or integrated as discussed in Succar and Poirier (2020) is key to better characterizing its potential. Figure 3 shows this scale which allowed the research team and the partner organization to settle on the best strategy to digitalize the business function or service, whereby not all functions required full digital twinning to digitalize.

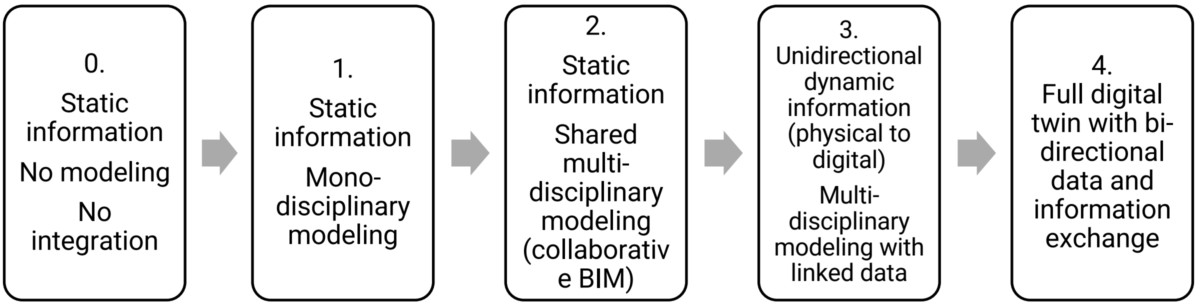

Figure 3 Potential of digital twinning as a function of the intensity of information modeling and integration and dynamism of its sources

The *relevance of digital twinning* is the level to which the digitalization of a specific business function is deemed important or necessary for the organization and can enable the organization to meet a strategic goal. Relevance is assessed on a 5-point likert scale, with 1 being little to no relevance, to 5, being highly relevant. Lastly, the expected *outcomes* stem from the application of DTs to the specific business functions and/or services according to the potential and relevance of the digital twinning process (i.e., the coupling). As per Davari and Poirier (2024), coupling outcomes include gaining Insight (e.g. a better understanding of a situation or a topic), improving Performance (e.g. ensuring that assets function properly, achieve their given objectives and produce the expected results), improve Quality (e.g. how well a product, service, or process meets the needs, expectations, or requirements of customers or users), allow Predictions (e.g. the forecasting of what will happen based on past and current data or trends), improve Sustainability (e.g. the ability to maintain or improve certain essential processes or practices over the long term without depleting the resources or causing harm to the environment), improve Resiliency (e.g. the ability to quickly recover from difficulties or adapt to challenging circumstances) and improve Compliance (e.g. the act of adhering to rules, standards, or laws set by governments, regulatory bodies, or internal policies).

Table 1 shows the completed framework from the perspective of intensity of information modeling and integration and dynamism of its sources (i.e., *potential of digital twining* identified by a number between 0 and 4) as they relate to business domains and business functions. The evaluation was mainly led by the research team with input by the partner organization. More specifically, each member of the research team indicated the potential of digital twinning for each business function based on the relevant literature and past experience. They then came together to identify and discuss points of convergence and divergence. The idea was to come to a consensus on the indicator of potential for each scenario in the matrix (Table 1). As a heat map, it shows where there is indeed potential for digitalization across the organization's business functions. Table 2 shows the assessment of relevance. This was performed by the directors from two different departments and, naturally, reflects their areas of interest. Both directors had many decades of experience in their respective domain, namely facility management and operations. However, certain areas of consensus emerged as to where digitalization through digital twinning would be beneficial and fit with the organization's overall strategy. When combined and completed the framework enables a prioritization of the business functions to be digitalized through digital twinning.

The results of the assessment of potential and relevance for digital twinning per business function were overlayed to better define the strategic fit enabling the guidance of the digital twinning process. Essentially, this overlay helps pinpoint where the organization should dedicate resources, plan implementation, and further develop its capacities as shown in figure 2. In this case, the top three functions identified were energy optimization, sustainability reporting and continuous commissioning. These were validated through triangulation with the organization's strategic planning documents.

Table 1 Potential of digital twinning

Domain	Function / Service		Planning	Monitoring	Simulation	Automation
Safety & security	Evacuation		1	3	1	
	Signaling		1	3	1	4
	Hazard		1	3	3	
	Incident		2	3	3	
	Fire risk register		2	3	3	4
	Asbestos control		1	3		
	Pest control		1	3	3	3
	Sanitation		1	3	3	3
	Emergency		1	3	2	
Real estate & property	Portfolio planning		2		2	
	Site selection		2		2	
	Transactions					
	Lease administration		1			
	Lease accounting		1			
	Tenant tracking					
	Building assessment		2	3	3	4
Capital projects	Program and scope		1			
	Land Use		1	3	2	
	Procurement		3	3	3	
	Vendor engagement		1			
	Schedule		1	3	3	3
	Resource		3	3	3	
	Responsible construction practice		1	3	3	
	Quality assurance and control		1	3		4
	Permit					
Facilities & assets	Facilities/Asset information (e.g., Plans, Models and Drav		2	2		2
	Data handover		1	2		2
	(Continuous) Commissioning		2	3	2	3
	Move and relocation		1			
	Strategic planning		1			
	Landscaping		2		2	
	Building user's guide/ Training		3			
	Decommissioning and EoL		2	3	2	
	Space and occupancy	Space management	1	3	3	
		Space requests	1			
		Space forecasting	1		1	
		Occupancy	1	3	3	
		Reserve meeting rooms	1	3	1	
		Hoteling	1	3	3	
		Room setups	1	3	1	
		Area measurment / calculation	1	3		4
		Space allocation	1	3	1	4
		Space assignment	1	3	1	4
		Space sutability assessment	1	3	1	4
		Space programming	1	3	1	4
		Post-occupancy evaluation	2	3	2	4
Operations & maintenance	Maintenance	Corrective and emergency	1	3		4
		preventive-inspection-scheduled	1	3		4
		predictive and condition-based	3	3	3	4
	Utility tracking			3	3	
	Helpdesk and Service Request			3		
	Grounds		1	3	3	3
	Janitorial		1	3	3	3
	Vendor		1			
	Warranty		2			
	Security/access/key		1	3		4
	Inventory and material (parts and tools)		1	3	3	3
	Logistics and supply		1	3	3	
	Cleaning and painting		1	3	3	
	Resource		1		1	
	Navigation and signaling		1	3	1	4
	HVAC controls		3	3	3	4
	Service and SLA			3	3	
	Performance		1	3	3	4
	Asset health		3	3	3	
	Asset condition		3	3		4
	Building automation		2	3	3	4
	Structural Health		3	3	3	

Table 1 (Cont.) Potential of digital twinning

Domain	Function / Service		Planning	Monitoring	Simulation	Automation
Environement & Sustainability	Energy	Consumption	3	3	3	4
		Heat requirement/Insulation	1	3	3	3
		Renewable energy	1	3	3	
		Power Density	2	3	3	4
		Grid Harmonization	1	3	3	
		Building Envelope/Thermal Bridge	1	3	3	3
		Energy optimization	3	3	3	4
	Light	Lighting control	2	3	3	4
	Air	CO_2 emissions reduction	1	3	3	
		Ozone creation potential	1	3	3	
		Ozone Depletion Potential (ODP)	1	3	3	
	Water	Water management	1	3	3	4
		Rainwater/Stormwater management	1	3	3	
		Acidification	1	3	1	
		Eutrophication	1	3	1	
	Materials	Recycled aggregates	1	3	1	
		Avoidance of pvc/ mercury etc.	1	3	1	
	Waste	Waste disposal	1	3	3	
	LEED/BREEAM certification		1	3	3	3
	Energy star integration		1	3	3	3
	Adoption to climate change		2	3	2	4
	Heat island reduction		1	3	1	
	Soil protection		1		1	
	Greening		1	3	3	4
	Sustainability reporting		1	3	3	3
Mobility & transportation	Electrical vehicles		2	3	2	4
	Wayfinding		1	3	1	4
	Elevators dispatch		2	3	3	4
	Location services		1	3	1	4
Human experience, health, wellness & services	Occupant comfort	thermal	3	3	3	4
		visual and lighting	3	3	3	4
		air quality	3	3	3	4
		acoustic	3	3	3	4
	User centered control		1	3	1	4
	Arrival experience		1	3	1	4
	Reserve equipement			3		
	Reserve vehicle			3		
	Visitor			3		
	Catering					
Knowledge & innovation	Documentation		2	2		2
	Requirement mgmt		1	3		
Contract	Contract preparation		1			
	Contract awarding/ tendering phase		1			
	Handover		1	3		
	Aftercare		1	3	3	
Finance	Payment processing					
	Chargebacks - FCA		1	3	3	
	Project financials		1			
	Cost (control and estimation)		1	3	3	
	Asset accounts		1			
	Operations cost		2	3	3	3
	Life cycle cost		2	3	3	3

The subsequent steps, once the business functions are identified and validated, were to map and characterize each business function. Part of this was done according to the approach outlined in ISO 29481 - Information Delivery Manuals (ISO, 2016) as they relate to the processes and exchange requirements, and to a lesser extent the transactions. Once the functions, their underlying processes and their data and information requirements were identified, a pilot project was undertaken on the targeted building. The pilot project focused on a flexible office space that the partner had implemented post-pandemic to increase its service offerings to its tenants. Two functions were piloted: occupancy/space reservation and comfort/indoor air quality. The DT architecture that was deployed for the pilot is shown in figure 4. As shown, a cloud-based environment was deployed to host and orchestrate the DT web app. Visualization was ensured through connection to an Autodesk Forge environment. The physical layer, including air quality (IAQ) and occupancy sensors were connected to the cloud environment through two mechanisms: through MQTT for the IAQ sensors as they were integrated into the BAS and through API webhooks for the occupancy sensors.

The intent of the pilot was to understand the types of insights that could be gleaned from the deployment and the costs associated to obtaining those insights. Given the predominantly cloud-based and service-oriented solution architecture, the costs for the deployment were relatively high. Moreover, the deployment was mainly in the realm of a digital shadow (or level 3 information modeling and integration per figure 3). Avenues to improve the occupant management process were explored, namely in a bid to optimize reservation of the flex spaces and combine that with the management of ventilation systems to improve energy efficiency and occupant comfort. Several challenges and roadblocks were met in attempting to deploy this solution, namely interoperability of sensor data, which will be documented elsewhere. Evaluation was performed by the partner organization’s team in collaboration with the research team. The solutions were presented, discussed and feedback was given during workshops through the action-design research process, validation and evaluation being a key part of this process. Upon evaluation, the partner organization were not entirely satisfied with the deployment given its limited scope and potential for cost optimization. As a result of this, the organization decided to pursue further investigation and strategic planning before committing to a more generalized approach.

5 Discussion and Conclusion

The development of DTs in the built asset industry is building on the foundations of the significant digitalization efforts undertaken over the past two decades, mainly articulated around BIM adoption and implementation. Rather than maintaining both domains, BIM and DT, as discreet and separate fields, the research project undertaken and presented in this paper sought to address these complementary approaches as a continuum that can be leveraged by organizations in the built asset industry to fulfill their strategic objectives. To do so, an action-design research project was undertaken with a large real estate company, on the implementation of a digital-twin of a large commercial complex in downtown Montreal, Quebec, Canada. To ensure that the development of the DT fit with the partner organization’s strategic plans and orientations, a structured approach was piloted and validated through a feedback loop with the organization’s upper management. This approach, which is supported through the framework presented in this paper, overlays the potential for information modeling and integration and the dynamism of is sources and the strategic fit of the digitalization per business function and for a given purpose. By instantiating the framework, the research team, in collaboration with the partner organization, was able to target specific business functions to be digitalized through the digital twinning process in a sensible manner. Once identified, each business function was characterized and mapped to detail the modeling and integration requirements and their underlying processes.

The research project has the following limitations. First, in establishing the strategic fit, only two executives were involved, which limited the coverage of perceived relevance for the digital twinning process. Future work should investigate extending this process across the organization in a structured manner. On the other hand, the intensity and dynamism of information modeling and integration identified per business function is debatable and requires further work to define and validate. The list presented in Table 1 can also be refined, revisited and extended to suit the organization’s needs, hence the extensible nature of the framework, it is not meant to be exhaustive at this point. Once identified and defined, the DT services were characterized but not fully implemented due to budget and time constraints. Moreover, from a technical perspective, the research project only partially implemented the targeted use cases given certain technical issues, namely related to interoperability with the buildings’ BMS and the digital twinning platform. Future work will focus on refining the framework and further validating it. It will also serve to define and develop the indicators of intensity and dynamism and how they are characterized, namely around functional and technical requirements.

Table 2 Perceived relevance of digital twinning as indicated by the participants

Domains	Business functions	Director 01	Director 02	Average
Environement & Sustainability	Energy optimization	4	5	4.5
Environement & Sustainability	Sustainability reporting	4	5	4.5
Facilities & assets	(Continuous) Commissioning	5	4	4.5
Safety & security	Evacuation	4	4	4
Facilities & assets	Facilities/Asset information	4	4	4
Environement & Sustainability	Waste disposal	4	4	4
Environement & Sustainability	Adoption to climate change	4	4	4
Mobility & transportation	Elevator dispatch	4	4	4
Finance	Operations cost	4	4	4
Safety & security	Asbestos control	5	3	4
Environement & Sustainability	Rainwater/Stormwater management	5	3	4
Environement & Sustainability	CO2 emissions reduction	1	5	3
Human experience, health, wellness & services	Air quality	1	5	3
Safety & security	Emergency	1	4	2.5
Facilities & assets	Occupancy	1	4	2.5
Operations & maintenance	HVAC controls	1	4	2.5
Operations & maintenance	Asset health	1	4	2.5
Environement & Sustainability	Lighting control	1	4	2.5
Finance	Life cycle cost	1	4	2.5
Safety & security	Fire risk register	4	1	2.5
Capital projects	Quality assurance and control	4	1	2.5
Operations & maintenance	Security/access/key	4	1	2.5
Environement & Sustainability	LEED/BREEAM certification	4	1	2.5
Environement & Sustainability	Energy star integration	4	1	2.5
Environement & Sustainability	Heat island reduction	4	1	2.5
Safety & security	Sanitation	1	3	2
Operations & maintenance	Janitorial	1	3	2
Operations & maintenance	Logistics and supply	1	3	2
Operations & maintenance	Service and SLA	1	3	2
Operations & maintenance	Performance	1	3	2
Operations & maintenance	Asset condition	1	3	2
Real estate & property	Building assessment	3	1	2
Capital projects	Schedule	3	1	2
Operations & maintenance	Warranty	2	1	1.5

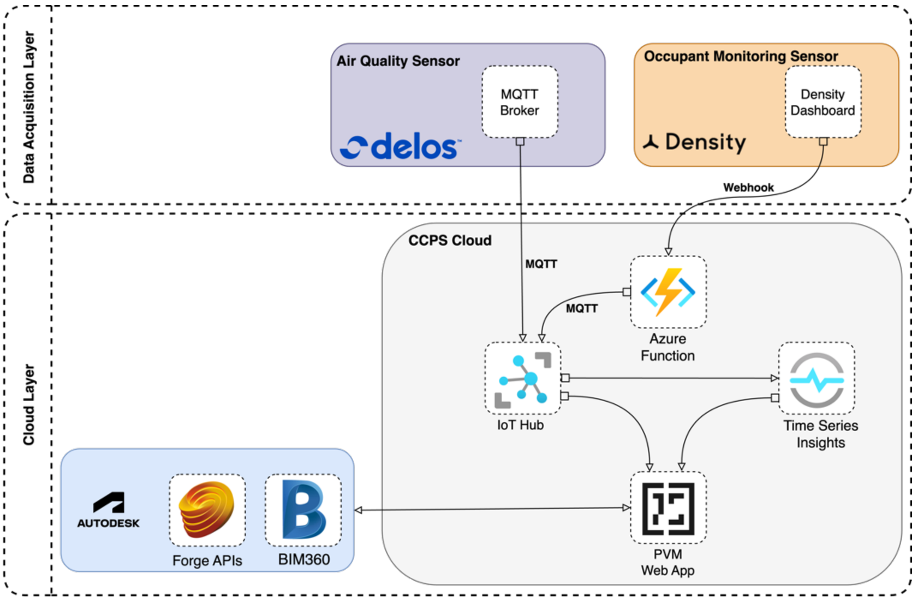

Figure 4 DT architecture for the pilot project

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