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AN ONTOLOGY FOR DIGITAL TWIN OPERATIONS AND MAINTENANCE USE CASES IN THE AECO INDUSTRY

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SUMMARY: *DTs have emerged as a promising technology for built assets. The purpose of the paper is to develop an ontology tailored to the DT operational uses, facilitating communication among stakeholders. A literature review was conducted to collect DT O&M uses from peer-reviewed papers to study existing DT ontologies and classification systems. Additionally, DT use cases were gathered through expert interviews and surveys. The existing ontologies were analyzed, and the DT use ontology was developed and refined using the BIM use ontology as a foundation. Internal and external validation methods were used to validate the ontology. Five primary DT use purposes are identified, including gathering, generating, analyzing, communicating, and realizing. The DT use purposes were further delineated into fifteen secondary uses. Additionally, a structured framework is proposed to consistently document and communicate DT use cases. This research contributes to academic and practical domains by offering a comprehensive understanding of DT uses.*

KEYWORDS: *Digital Twins, Use Cases, Ontology, Cyber-Physical Systems, Operations and Maintenance.*

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1. BACKGROUND

Studies indicate that the Operations and Maintenance (O&M) costs associated with a building are commonly higher than three times the initial construction costs (Fuller, 2016). Implementing Digital Twins (DTs) can potentially enhance facilities' operational efficiency. Furthermore, it creates the opportunity to lower O&M costs and create sustainable buildings and infrastructure. By definition, a digital twin of an asset is "a fit-for-purpose and intelligent virtual representation of it synchronized at specific frequencies, with an existing or planned connection between the virtual and physical twin that may include analysis and the ability to actuate physical changes from the virtual twin." (Ghorbani and Messner, 2024)

There has been an increasing interest in Digital Twins (DTs) within the Architecture, Engineering, Construction, and Operations (AECO) domain, drawing attention from both academic and industry stakeholders. On the academic front, a notable increase in peer-reviewed DT publications is evident in research trends (Emmert-Streib et al, 2023). Over the past five years, various national and international initiatives have been undertaken to facilitate the integration of DTs into the AECO industry, such as the National Digital Twin Program in the UK, the Digital Twin Consortium, and the Digital Twin Integration subcommittee in the National Institute of Building Sciences (NIBS).

1.1 Current State of Digital Twin Adoption in the AECO Industry

Several DT uses and use cases have been documented in the literature in recent years. It is critical to distinguish a DT use from a DT use case. A DT *use* provides a common language for communicating how DTs are applied during the life of an asset (e.g., capture conditions). A DT *use case* is a specific application of a DT use [that includes a method and desired outcome] focused on adding value to the project(s) and organization(s) (e.g., capture conditions to create an energy model using equipment sensors and deep learning algorithms).

DTs can be implemented throughout the lifecycle of an asset, from the planning (Schrotter and Hürzeler, 2020) to the design phase (Ozturk, 2021; Yang and Lv, 2022), to the construction phase (Nour El-Din et al, 2022; Salem and Dragomir, 2022; Zhang et al, 2022) , and to the operations (Hodavand et al, 2023; Jiang et al, 2023; Lu et al., 2020a). Examples of DT O&M uses include fault detection (Hodavand et al, 2023; Hosamo et al, 2023a; Lu et al, 2020b; Xie et al, 2023) ; predictive maintenance (Ahmad and Alshurideh, 2023; Arsiwala et al, 2023; Hosamo et al, 2023b) ; asset monitoring (Akanmu et al, 2014; Boddupalli et al, 2019; Edwards et al, 2023; Futai et al, 2022; Nguyen et al, 2022); and asset performance evaluation (El Mokhtari et al, 2022; Hosamo et al, 2023a) . While there are many DT use cases documented in the literature, most of them are at the research level and lack real-life DT implementations. The limited prevalence of real-world DT implementations can be partially attributed to the fact that the AECO industry is still in the early stages of adopting DTs. One limiting factor is a lack of a standardized structure and language to clearly describe DT use cases.

An ontology can greatly enhance communication among various stakeholders by providing standardized language and a common framework. An ontology, as defined by Noy and McGuinness (2001), is "*a formal and explicit representation of concepts within a specific domain, detailing the properties and attributes of each concept, along with any associated constraints.*" In a manner similar to the adoption of the BIM use ontology in the development of the BIM execution planning process, the DT use ontology will be leveraged to enable a structured and methodical approach to DT design and planning.

1.2 Existing Digital Twin Use Reviews and Classification Systems

Use cases, which focus on the purpose a DT serves, are fundamental to DT implementation. While no international standard for DT use cases exists yet, the ISO 23247 series provides a valuable framework for implementing DTs in manufacturing while underscoring the importance of use cases. For instance, Shao (2021) leverages the ISO 23247 series to outline use case scenarios in manufacturing, highlighting its relevance for structured DT adoption. A number of studies have reviewed DT uses in the AECO industry. Ivanov et al. (2020) investigated technologies that can be used to build a DT of a city. They provided examples of O&M DT uses for city DTs, such as monitoring the urban environment, emergency response, design assessment, risk identification, pollution control, microclimatic weather forecasting, energy consumption rationalization, snow removal operation optimization, and monitoring bridge conditions. Liu et al. (2021) provided a summary of industrial DT uses through a systematic literature review of 240 peer-reviewed papers. They identified several O&M DT applications, including predictive maintenance, fault detection and diagnosis, asset monitoring, performance prediction, virtual testing, real-time monitoring, asset management, and process evaluation and optimization. Jiang et al. (2021) identified several O&M uses for DTs in the Civil Engineering sectors. These uses included defect detection, asset monitoring, analysis and diagnosis, decision-making, automatic control of the assets, retrofitting and demolishing, and comprehensive asset management.

Similarly, Ozturk (2021) studied the patterns, gaps, and trends in DT research in the AECO Industry through a bibliometric search, a scientometric analysis, and a mapping of the identified papers. Among all the research topics they identified, the following are closely related to O&M DT uses: building lifecycle management and information-based predictive maintenance. In another study, Shahzad et al. (2022) reviewed DT applications in the built environment. Their methodology consisted of a literature review and semi-structured interviews. They identified many DT applications, including smart cities, design decision-making, product manufacturing, real-time construction progress monitoring, and facilities management. While these studies contribute to the body of knowledge by providing a list of DT uses, they do not provide a systematic classification structure for DT uses.

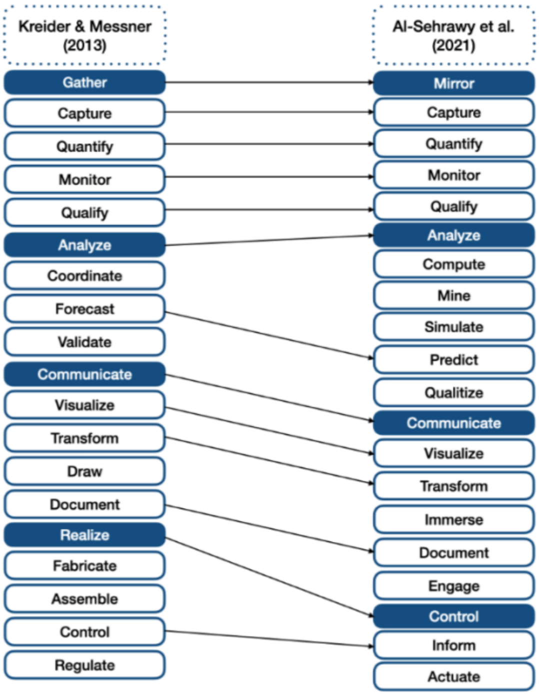

Figure 1: Mapping of the classification system developed by Al-Sehrawy et al. (2021) (on the right) to the BIM Use ontology by Kreider and Messner (2013) (on the left).

In the AECO industry, widely adopted ontologies have been developed to support the planning and implementation of technologies. Among those ontologies, the BIM use ontology by Kreider and Messner (2013) has an approach that can be adapted for DT ontologies due to the commonalities between BIM and DTs. The BIM use ontology provided a common language for defining BIM uses. The research methodology to develop the ontology consisted of six main steps: (1) defining domain and scope, (2) acquiring domain knowledge, (3) documenting domain terms, (4) integrating domain terms, (5) refining and validating the ontology; and (6) documenting the final ontology. Their ontology classified the BIM uses based on the purpose and characteristics of the BIM uses. The five primary categories were Gather, Generate, Analyze, Communicate, and Realize. The BIM use ontology was then adopted by the U.S. National BIM Standard (NBIMS), which is the primary standard for BIM implementation in the U.S. The DT use ontology will be used within the creation of a design and planning process for DTs, similar to how the BIM use ontology is used for BIM implementation planning.

A few studies have provided classification systems for DT uses. Al-Sehrawy et al. (2021) developed a classification system for DT uses in Urban Planning, building upon Kreider and Messner's four primary use classes: Mirror [Gather], Analyze, Communicate, and Control [Realize]. Figure 1 depicts the mapping of their classification system to the BIM Use ontology. Within the Gather class, they identified four secondary classes: capture, monitor, quantify, and qualify. The Analyze class encompassed five secondary classes: compute, mine, simulate, predict, and quantify. The Communication class included visualize, immerse, document, transform, and engage, while the Control class comprised inform and actuate.

In another study, El Jazzar et al. (2020) conducted an extensive literature review to assess the state of DT implementation in the construction industry, offering a classification framework. Their framework featured four core actions: capture (from the physical facility), analyze, capture (from the DT), and act (controlling the physical facility from the DT). These actions align with the classes in the BIM use ontology. While these classification systems offer valuable insights, they do not provide a comprehensive ontology to accommodate existing DT O&M uses.

1.3 Knowledge Gaps and the Purpose of the Study

Throughout the literature, there was no comprehensive standardized ontology or common language for documenting and communicating DT for implementing DTs in the AECO industry. This lack of a unifying ontology not only impedes the adoption of DTs but also hinders stakeholders from gaining a comprehensive understanding of the breadth and potential of DTs. This research addresses these knowledge gaps by proposing a structured framework for the organization and communication of DT O&M uses, fostering clarity, creativity, and cohesiveness within the AECO industry. The purpose of this paper is to define an ontology for DT O&M uses to facilitate the planning and implementation of digital twins in the AECO industry. The ontology can subsequently be leveraged for the design and planning of DTs, assisting practitioners and owners in identifying and selecting high-value use cases.

2. RESEARCH METHODS

A structured approach was leveraged to develop, validate, and document the DT use ontology (see Figure 2). Each step is described in the following sections.

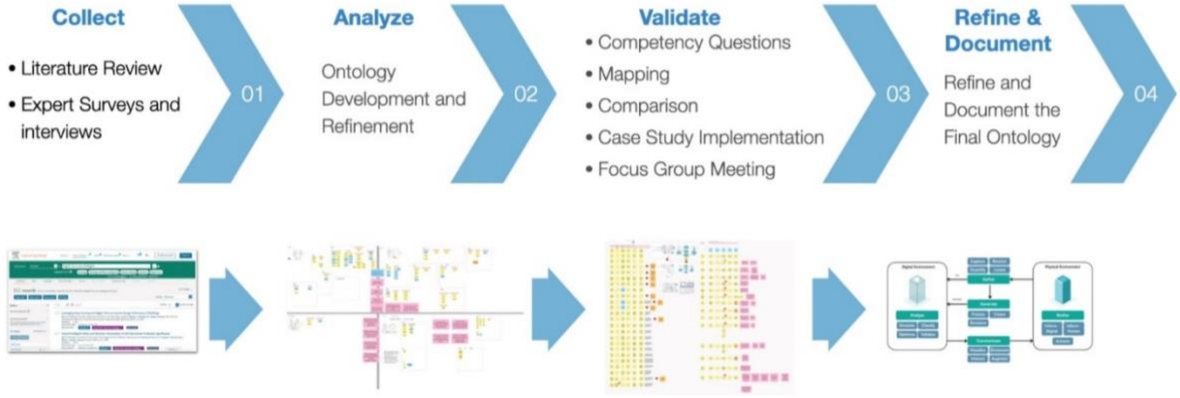

Figure 2: Research Design (lower icons are for illustrative purposes only).

2.1 Collect: Literature Review

A systematic literature review was completed to identify the existing DT O&M uses and ontologies (see Figure 3).

This review used three major engineering databases, including Compendex, Inspec, and Knovel, to search for relevant literature. The search covered all papers published from January 2014 to January 2024, using keywords specified in Figure 3. Exclusion criteria included non-English papers, duplicates, non-peer-reviewed publications, and those not addressing DT O&M use cases. Additionally, papers published in predatory journals were excluded, with Beall's list of potential predatory journals and publishers to filter out such sources (Beall, 2023). Following this rigorous evaluation process, 150 papers were deemed suitable for analysis and synthesis. The use cases in these papers were documented using the exact terminology as presented in the original manuscripts.

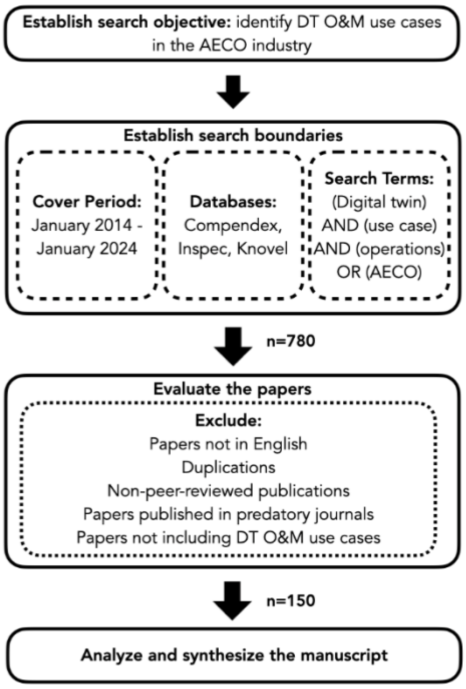

Figure 3: Systematic Literature Review Methodology.

2.2 Collect: Expert Surveys and Interviews

We conducted surveys and semi-structured interviews to gather additional DT O&M use cases. The objective of these targeted surveys and interviews was to collect additional DT use cases, rather than to provide a comprehensive representation of the entire industry. Prior to data collection, an Institutional Review Board (IRB) application was submitted, reviewed, and approved. Purposeful and snowball sampling methods were employed to assemble a diverse group of participants. An initial list of 40 industry and academic DT experts was compiled through our professional network. Participants were selected based on specific eligibility criteria to ensure relevance and expertise in the field of DTs. Academic participants were required to have peer-reviewed publications or active research projects related to DTs. Industry participants needed to be engaged in real-life DT projects or be active members of national or international professional DT societies. The selection encompassed participants ranging from thought leaders in the DT domain to individuals having experience with DTs, though not necessarily recognized as leaders.

The survey link was sent to the individuals on the list. The individuals were asked to complete the survey, and there was a question at the end to indicate whether they were interested in a follow-up interview. Surveys were collected anonymously. However, if a participant indicated an interest in a follow-up interview, they would voluntarily provide their email address so they could be contacted to set up the interview. For snowball sampling, there was a question at the end of the survey to ask if the participant knew any other DT experts that could be contacted for this study. The survey questions can be accessed at: https://scholarsphere.psu.edu/resources/e3057cf0-c4ba-4195-a560-3228fcea9c6b

The survey was administrated via Qualtrics and consisted of three main sections: demographics, DT definition, and DT O&M use cases. As the focus of this paper is on DT O&M use cases, only the analysis related to the use case questions is included. The questions regarding use cases were open-ended, allowing respondents to provide detailed descriptions. Survey participants were asked to identify three to seven DT use cases that they considered of high value during the Operations phase of a facility.

The survey was sent to 40 individuals, resulting in a 55% response rate with 22 completed responses. The respondents included 14 individuals from industry and 8 from academia. Academic participants were exclusively faculty members with an average experience of 22.9 years. Industry participants encompassed various roles, such as executives, technology specialists, project engineers, and architects, with an average of 17.6 years of experience (see Figure 4).

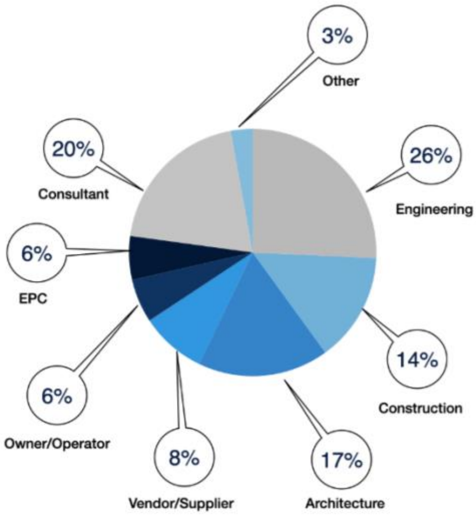

Figure 4: Primary Categories of Work for Industry Participants' Organizations.

Industry participants were from diverse sectors, including commercial buildings and healthcare, manufacturing and life sciences, industrial facilities, transportation and infrastructure, residential, and educational institutions (see Figure 5).

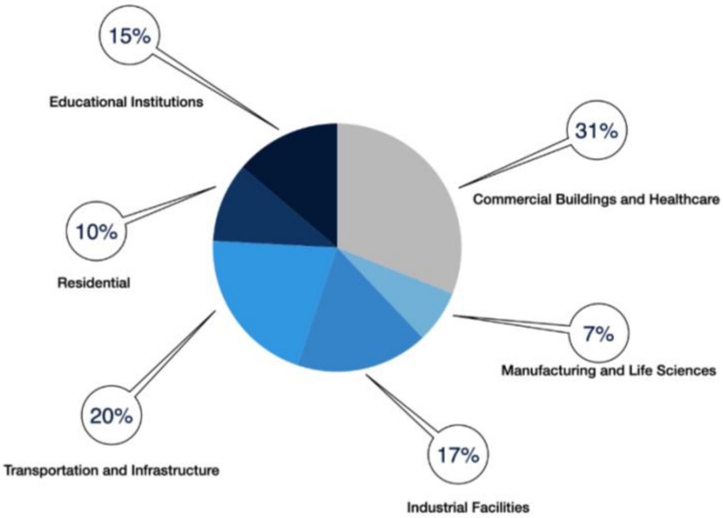

Figure 5: Primary Capital Facility Industry Sector for Industry Participants' Company.

Industry participants were asked about their organizations' level of pursuing DTs. The ratings of the 13 industry participants were very low (1 participant), low (3 participants), medium (4 participants), high (1 participant), and very high (4 participants). This question was specific to industry participants.

In addition to surveys, semi-structured interviews were conducted, which included questions derived from participants' survey responses. Of the 19 interviews, 15 were conducted via video calls (using Microsoft Teams), each lasting approximately 30 minutes, and the remaining four interviews were conducted in person. Interviews were transcribed using an automatic AI transcription tool (Otter.ai). An online mapping tool (MindMeister) was employed for initial note-taking and results documentation. NVivo 14 software was used to code and analyze interview transcripts. Data saturation was used as the criterion to determine the number of interviews conducted. The process continued until no new use cases emerged from the interviews, including that additional data collection was unlikely to provide further insights. Ultimately, 137 use cases were gathered from surveys and interviews, which were documented in a spreadsheet for further analysis.

2.3 Analyze: Ontology Development and Refinement

In the initial stages of developing the DT use ontology, a critical step involved the analysis of the identified ontologies. These ontologies were analyzed to evaluate their suitability and relevance to the DT domain. Following the selection of the most pertinent ontology, its components and attributes were documented. This documentation not only encompassed the classes and relationships but also delved into the finer details, ensuring a comprehensive understanding of the ontology's structure. The systematic extraction and documentation of these components served as the foundation for the subsequent adaptation and customization of the ontology to align with the specific O&M uses and requirements of DTs, ultimately resulting in an ontology fine-tuned to the unique characteristics of DTs in various applications.

After analyzing the existing ontologies, the first step to creating a robust ontology tailored for the context of DTs in AECO was to select an existing ontology that is relevant and aligns with the domain of interest. The BIM Use ontology by Kreider and Messner was selected as the basis for building the ontology. The choice of ontology provided a structured foundation for building upon, reducing redundancy, and enhancing interoperability. The selected ontology needed to be comprehensive enough to capture the essential aspects of DTs and their use cases. With the chosen ontology as the starting point, the next step was to structure the DT's O&M use cases based on this ontology. This process involved identifying how different classes and concepts in the ontology related to specific functions, capabilities, and features of DTs. This structural alignment ensured the ontology remained coherent with the O&M DT use cases.

In some instances, the selected ontology required modification to better address the specific needs of DTs. This adaptation process involved using the BIM use ontology as a foundation, followed by extensive enhancements and customizations to extend its applicability to the DT domain. Notably, secondary purposes such as "interact" and "inform" were introduced to capture the diverse DT use cases. The "interact" purpose facilitates scenarios where the DT notifies humans about conditions requiring intervention. For instance, if a DT detects anomalies in a mechanical system, it can alert a technician, who can then investigate and address the issue. This adaptation highlights a key divergence from the BIM use case ontology due to the distinct nature of BIM and DT. Unlike BIM, which lacks real-time data capabilities, DTs can leverage live data to generate alarms for anomalies, enhancing their use in real-time monitoring and response.

Table 1: Internal and External Validation Methods Used in this Research, along with their Descriptions.

	Method	**Description**
Internal	*Competency Questions*	Competency questions are a set of questions that the knowledge within an ontology should address (Uschold and King, 1995).
	Mapping	Associating original DT terms with classes within the ontology.
	Comparison	Comparing the DT use ontology with formal ontology standards and structures.
External	*Case Study Implementation*	Mapping the DT uses from case studies to classes within the ontology.
	Focus Group Meeting	Meeting with a group of industry members to evaluate the ontology in a structured manner.

Definitions for each ontology class were crafted to facilitate a clear understanding of the ontology in the context of DTs. These definitions described the class's meaning and relevance in the DT domain. To ensure comprehensive coverage, the definitions were developed using the breadth of knowledge encapsulated in examples of each class. This approach enabled a deeper understanding of the practical applications and nuances associated with each class. These definitions help users and stakeholders interpret the ontology and its classes accurately, fostering a shared understanding of the model's semantics. In addition, other terms that were used in the literature for each class were documented for each class and subclass.

Finally, a comprehensive documentation of the ontology was created that included details about the ontology's structure, classes, subclasses, and definitions (see Section 3.2.).

2.4 Validate: DT Ontology Validation

The validation process consisted of internal and external validation methods. Internal methods consisted of competency questions, mapping, and comparison. External methods included case study implementation and a focus group meeting (see further descriptions in Table 1).

2.4.1 Competency Questions

The validation method using competency questions ensured that the DT use ontology met its intended goal of providing a shared vocabulary for DT uses, including terms, classes, and definitions. The competency questions used for this purpose included the following: What are the specific DT uses? What are the definitions of the DT uses? What are the classes of the DT uses? What is the class hierarchy of the DT uses? What is the relationship between one DT use and other DT use(s)?

2.4.2 Mapping

The ontology is structured around several purposes of using DTs to support O&M. A set of 137 use cases (gathered through interviews and surveys) was reviewed, and each of the use cases was placed into a specific DT use purpose. For most of the use cases, the mapping was accomplished easily. However, there were some instances where the DT use would belong to more than one purpose. After further analysis, we determined that these use cases were more complex and could be dissected into multiple use cases. Therefore, we introduced the concept of compound DT uses.

2.4.3 Comparison

An ontology comparison was conducted to ensure that all rules and standards of ontology creation were adhered to within the DT use ontology. These rules include term bias, class cycling, multiple inheritance, secondary class numbers, and ontology expansion. To address term bias, it was essential that terms did not unintentionally favor meanings from the industry. For instance, the initial use of the term "process" as a secondary class for transforming raw data into meaningful data was changed to "transform" to avoid confusion with design and construction processes. Addressing class cycling involved comparing definitions to ensure that primary and secondary classes did not overlap, thus preventing a term from being part of the definition of its primary class.

Multiple inheritance was another critical aspect, where secondary classes should not belong to multiple classes. This challenge appeared when certain DT uses could belong to more than one superclass. Upon further analysis, these cases were identified as more complex DT uses and were broken down into several DT uses, leading to the proposal of the compound use structure. Regarding secondary class numbers, the DT use ontology followed the rule of having at least two and no more than twelve secondary classes for each primary class, adhering to guidelines from Noy and McGuinness (2021). Lastly, ontology expansion was considered to ensure that while the DT use ontology had a well-defined scope, it also allowed for future expansion. Given the rising use of DTs and the emergence of new uses, the ontology was designed to be flexible and capable of accommodating future developments. Specifically, if new DT uses are identified, they should be initially compared to the primary classes within the existing ontology to determine their appropriate classification. This process involves determining whether the new use necessitates the creation of a unique primary or secondary class and whether existing classes require revision in response to these changes. Such a structured approach ensures the ontology remains robust and relevant as the field of DT continues to evolve.

2.4.4 Case Study Implementation

To further validate the DT use ontology, three case studies from real-life DT projects were selected, including the University of Birmingham, California Community College, and YVR airport. Publicly available use cases from each of these projects were mapped to the ontology use purposes, and each use case was named following the proposed use case naming convention. Specifically, four use cases from the University of Birmingham DT, twelve use cases from YVR airport DT, and seven use cases from the California Community College DT were used for this validation. Mapping the ontology against these real-life DT projects ensured its applicability and relevance for industry practitioners.

2.4.5 Focus Group Meeting

To add another layer of validation, a focus group meeting was conducted with six industry experts, four of whom have worked on DT projects. During this 1.5-hour video conference meeting, the DT use case naming convention, the DT use ontology, and the compound use case structure were presented to participants through Mural (an online interactive platform). The content of each section was presented for review, with participants providing verbal opinions and written feedback directly on the Mural board. Prompts such as "Does this seem like a reasonable approach?" or "Do you think you can adopt it?" were included to stimulate discussion among participants. Notes were taken during the meeting, and afterward. These notes (from verbal feedback) were added to the Mural. Comments were then grouped based on similarity, and modifications were made where appropriate.

3. RESULTS AND DISCUSSION

This research classifies DT uses primarily according to their purposes (see Figure 6). The flexibility of this classification system allows for customization at different levels of specificity, accommodating the nuanced requirements of various DT applications. By delineating purposes and specifying attributes, this ontology contributes to a more refined and adaptable approach to defining and implementing DTs.

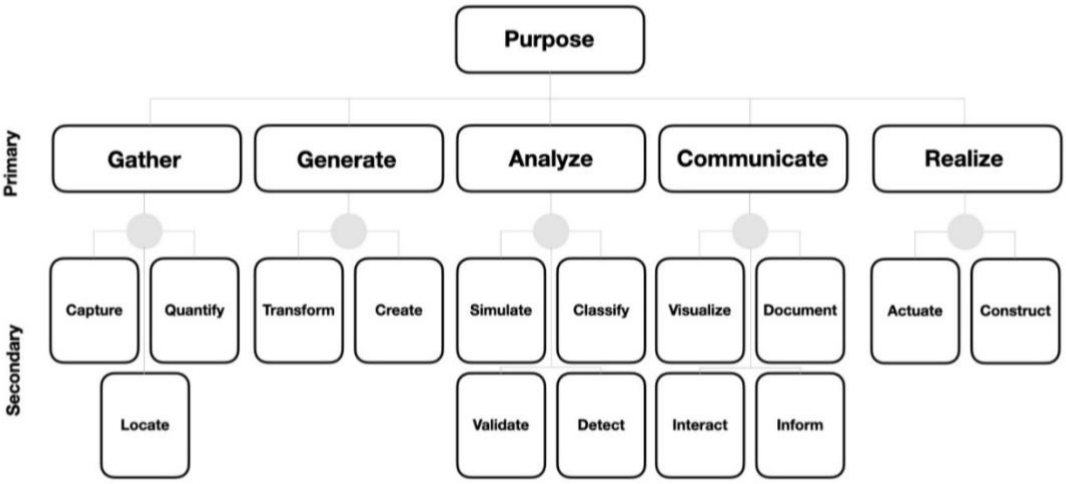

Figure 6: Primary and Secondary DT Use Purposes.

Within the primary categories, a nuanced understanding is achieved through numerous secondary categories that provide a detailed specification of the purpose of DT uses.

3.1 DT Use Case Name Structure

For the name of the use cases, the following structure was developed, which aligns with the BIM Use Definitions section of the US National BIM Standards V4 (2023) (see Figure 7). This naming structure provides the industry with a standardized approach to naming the DT use cases, thereby facilitating more effective knowledge sharing and enhancing consistency across the field.

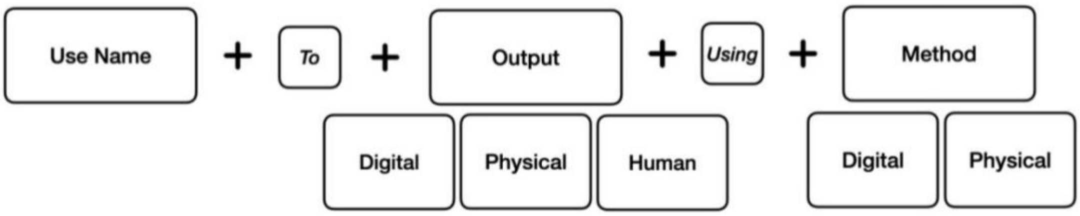

Figure 7: DT Use Case Name Structure.

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The use case name includes the use name, the output of the DT use case, and the method to achieve the DT use. The output can be categorized as digital (e.g., a change in the DT system), physical (e.g., a change in the physical environment), or human (e.g., informing a user). Similarly, the method can be digital (e.g., software) or physical (e.g., sensors). Table 2 provides possible values of different types of outputs and methods for each purpose category. It should be noted that each DT use case should have at least one output and one method.

Table 2: Potential Output and Method Types for Each DT Use Purpose Category.

Purpose	**Output - Digital**	**Output - Physical**	**Output - Human**	**Method - Digital**	**Method - Physical**
Gather	X		X		X
Generate	X			X	
Analyze	X		X	X	
Communicate	X	X	X	X	
Realize	X	X	X	X	

3.2 DT Use Ontology

Table 3 presents primary and secondary purposes for DT uses, along with their objectives. We have also captured other words used in the literature in the “also known as” column.

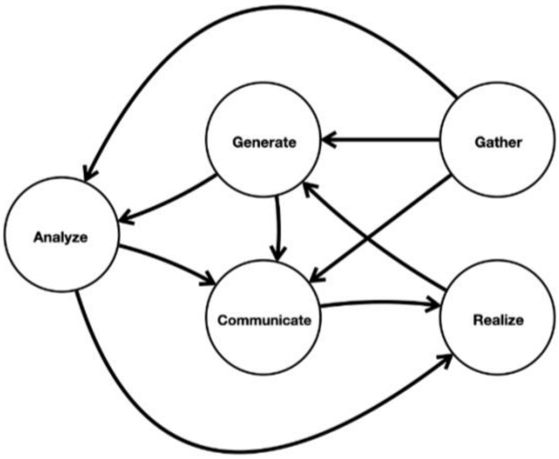

Figure 8: Relationships between Different Purposes in a Compound DT Use.

3.3 Compound DT Uses

Within DT uses, there is a variety of levels of complexity. Some DT uses encompass multiple tasks, necessitating a nuanced approach to their implementation. To address this complexity, the proposed ontology systematically dissects compound uses into distinct components. As a case in point, the compound use of “wayfinding” involves a series of tasks, such as identifying the user’s location, analyzing the path to the destination, visualizing the desired route, and communicating it to the user. This research clarifies the interconnected nature of these tasks, where the output of one step serves as the input for the subsequent one (see Figure 8). In the example use case of wayfinding, the identified location becomes the input for analyzing the path, and the path information is subsequently utilized for visualizing the desired route. This structured framework enhances users’ understanding of the implementation process, fostering a systemic approach to DT uses.

As illustrated in Figure 8, there can be various combinations of DT uses to make a compound DT use. The possible relationships (i.e., arrows in the Figure) were created based on the compound uses found in our datasets that contain use cases from the literature, surveys, and interviews. Each arrow indicates a potential relationship between two DT uses in a compound DT use. As an example, a DT use from the Gather category can be the predecessor step in a compound use, followed by a DT use from the Generate, Analyze, or Communicate categories.

Table 3: DT Use Purposes and Objectives.

Purpose	Objective	Also Known As
Gather	To collect data	Collect, Acquire
Capture	To collect data along with the metadata	Collect, Scan
Quantify	To measure and determine the quantity or numerical value of the object of interest	Measure, Calculate
Locate	To identify the location of an asset or a user	-
Generate	To create meaningful and machine-readable information from raw data	Produce
Transform	To process or organize raw data into meaningful information or knowledge that can be used in a digital twin	Clean, Structure, Organize
Create	To produce insightful analytical representation(s) of asset data	Generate, Build
Analyze	To create insights regarding an asset, user, or built environment using analytical methods.	Evaluate, Examine, Assess
Simulate	To predict the future state of an asset using current or historical data	Predict, Forecast, Foresee
Classify	To categorize information using current or historical data	Categorize
Validate	To check or prove the accuracy of information	Check, Confirm, Verify
Detect	To establish or indicate what something is	Identify
Communicate	To exchange information between the digital twin and user(s)	Exchange
Visualize	To create a visual representation of an asset	Review
Document	To create a record of the desired information pertaining to an asset	Specify, Submit, Schedule, Report
Interact	To engage and communicate with the digital environment	Augment, Annotate
Inform	To provide information to a human or digital controller	Notify
Realize	To control or make changes in an asset	Implement, Execute, Modify, Adjust, Reconfigure
Actuate	To translate digital signals into physical actions	Activate, Control, Manipulate
Construct	To create or add to the physical environment through digital control and automation	-

4. DT EXAMPLE – CALIFORNIA COMMUNITY COLLEGE

To demonstrate how the DT use ontology applies to real-life DT projects, a demonstration example is presented here. The Foundation for California Community Colleges requires a comprehensive and authoritative inventory of the 90 million square feet of buildings and spaces across its 72 districts to effectively budget for future capital projects, space inventory and utilization, and facility condition. To address the need to align with other DT systems, they created an application programming interface (API) to access their inventory data and connect to other systems, such as operations and maintenance. These DT systems capture and manage detailed information on buildings and spaces linked to Building Information Modeling (BIM) data, enabling administrators and state officials to make informed decisions. The web-based system links graphical representations of buildings to their data, allowing authorized users to view, update, and analyze information. The use of DT throughout the lifecycle of educational spaces enhances the educational environment and supports strategic facility management.

Our proposed ontology was used to map out the use cases within these DTs, and the following compound uses were identified:

1. Manage spaces
2. Manage assets

Figure 9 and 10 depict the DT systems and their interfaces.

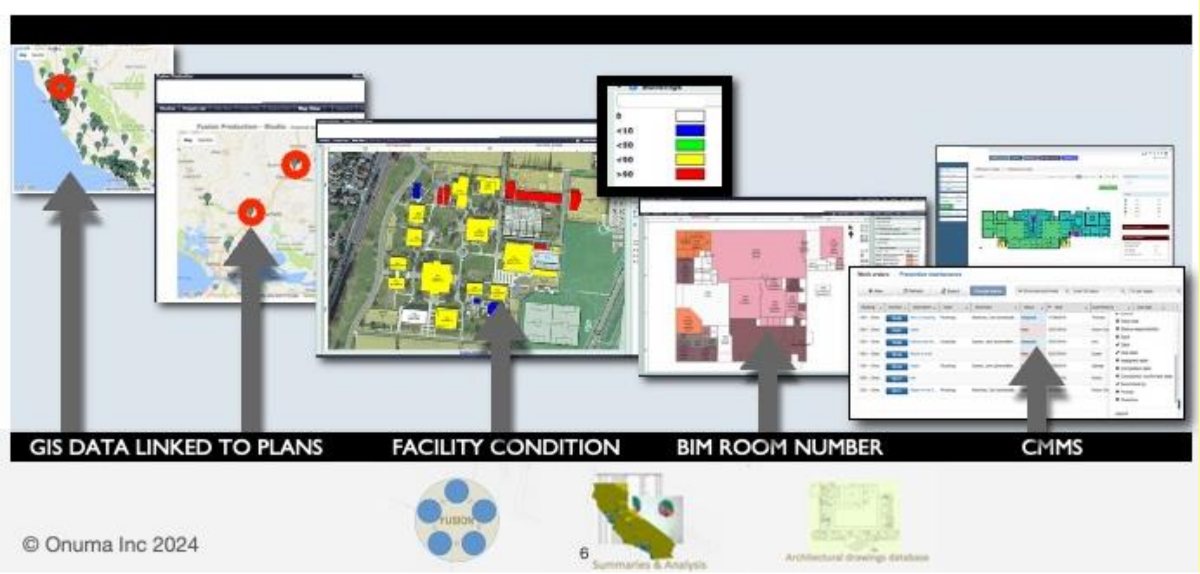

Figure 9: DT Systems in California Community College Case Study.

Figure 10: DT Systems User Interfaces in California Community College Case Study.

The breakdown of these compound use cases is presented in Table 4. We have included the minimum required information for these use cases. For a comprehensive schema for DT use case documentation, refer to (Ghorbani et al, 2024).

5. SCALABILITY AND EXTENSIBILITY OF THE PROPOSED ONTOLOGY

The proposed ontology is designed to be scalable and extensible, accommodating the evolution of technologies and the emergence of new use cases over time. This adaptability ensures that the ontology remains relevant and effective as the DT landscape evolves. A key feature of the ontology is its categorization of DT use cases based on their purpose. This structure allows for a systemic analysis of use cases, ensuring that they are evaluated and organized according to the specific objectives they fulfill. As new use cases emerge, they can either be classified under existing categories or necessitate the addition of new categories to the ontology, maintaining its relevance and applicability. For instance, artificial intelligence (AI) is a rapidly evolving technology that continues to enable novel capabilities within DT systems. Depending on the purpose of the use case, AI-driven applications can be categorized under various existing classes in the ontology. A notable example is the use of AI for predictive maintenance. Predictive maintenance, as defined within the ontology, is a compound use case that encompasses multiple [single] uses, such as capturing faults, creating predictive models, simulating faults, and informing users. In this context, AI is employed for creating predictive models and simulating faults, demonstrating its integration into the existing ontology structure.

Similarly, as DTs progress towards autonomous systems, new use cases are anticipated to emerge. These use cases will either align with the existing categories or necessitate the creation of new ones to accommodate to expanding functionality of DTs. This flexibility underscores the scalability and extensibility of the ontology, ensuring that it can adapt to advancements in technology and the continuous evolution of the AECO industry. By providing a structured framework that evolves alongside technological progress, the ontology serves as a dynamic tool for categorizing and understanding DT use cases, ultimately supporting their effective implementation and integration into real-world applications.

Table 4: DT Use Cases in California Community College Case Study.

#	DT Use	Output - Digital	Output - Physical	Output - Human	Method - Digital	Method – Physical
1	**Compound Use: Manage Spaces**					
1.1	Capture space data	Create a dashboard	X	X	GIS and BIM data	X
1.2	Visualize building plans	Link space inventory, facility conditions, and plans	X	X	BIM, GIS, and Computerized Maintenance Management System (CMSS)	X
1.3	Communicate space data	Create reports and a dashboard	X	Inform users	APIs	X
1.4	Interact with dashboard	Update space information	X	X	APIs	X
2	**Compound Use: Manage Assets**					
2.1	Capture asset data	Create a dashboard	X	X	X	Sensors
2.2	Visualize asset data	Update model information	X	X	CMMS and APIs	Sensors
2.3	Inform users	X	Fix the problem	X	CMMS and mobile interfaces	X

6. CONCLUSIONS

In conclusion, this study addresses the challenges faced by the AECO industry in implementing DTs. One prominent challenge identified is the absence of standardized language for documenting and communicating DT use cases. To fill this gap, our research contributes a comprehensive ontology tailored to DT O&M uses within the AECO domain. The proposed ontology encompasses categories that outline DT use purposes along with essential attributes defining specific use cases. The primary use purposes identified (gathering, generating, analyzing, communicating, and realizing) serve as a foundational framework for understanding DT use cases, each further branching into several secondary purposes. Moreover, recognizing the varying levels of complexity, some use cases are dissected into multiple, more granular uses, and compound use cases emerge by combining two or more use purposes.

Another contribution of this research is the use case naming structure, incorporating elements such as use name, output, and method. This structure not only provides clarity but also facilitates a systematic approach to understanding and categorizing DT use cases. The practical implications of this research are substantial. By providing a standardized framework for documenting and communicating DT use cases, the proposed ontology addresses a critical need within the AECO industry. It offers a common language to enhance collaboration, knowledge sharing, and innovation among stakeholders. More importantly, the ontology serves as a foundational component for developing a systemic procedure for DT design and planning. As the industry continues to leverage DTs, the adoption of this ontology will help to streamline communication and promote a more efficient and effective implementation of DTs in various operational contexts.

LIMITATIONS AND FUTURE WORK

The study acknowledges several limitations that may impact the generalizability of the findings. Firstly, DTs are still in the early stages of adoption within the AECO industry, resulting in a limited number of documented use cases. This nascent stage of adoption restricts the breadth and depth of the available data, potentially affecting the comprehensiveness of the insights derived from the study. Additionally, most interviewees were from the US, UK, and Canada, and only papers written in English were analyzed, which may introduce linguistic biases. Additionally, as the industry continues to integrate more DTs and as research in this area progresses, it is anticipated that more mature use cases will emerge. Consequently, future developments may lead to the evolution of these use cases, which could provide a more robust foundation for refining and expanding the classes discussed in this paper.

Future work includes the continuous refinement and standardization of the ontology to adapt to emerging DT applications. As the field of DT rapidly evolves, it is crucial to update the ontology to reflect new uses and ensure it remains a comprehensive framework. Additionally, the ontology will be leveraged to develop a robust library of use cases, which will serve as a valuable resource for the design and implementation of DTs. By maintaining an up-to-date ontology, we can support the development of innovative DT solutions and contribute to the advancement of this transformative technology. The full list of use cases can be accessed at https://www.cic.psu.edu/the-uses-of-digital-twins/. A representative sample of the DT uses, along with methods and outputs, are presented in Table 5 in Appendix A. An online form is available in the online library platform for submitting emerging use cases, enabling continuous analysis and refinement. The ontology is designed to evolve, allowing for the addition of new purposes or categories as technologies, such as AI, advance. For instance, as AI capabilities grow, it may unlock new DT use cases that could either align with existing categories or necessitate the creation of new classes.

The goal of this ontology is to provide a structured framework to guide the planning stage of DT adoption, serving as a foundational component in a comprehensive DT design and planning process. By integrating the ontology with the twinning process, this approach enhances the understanding of DT use cases, bridging the gap between academic research and practical implementation. This approach facilitates knowledge transfer from academia to industry while offering clear guidance for researchers and practitioners on effectively designing and implementing DTs. A major focus of the ontology is DT use case planning, which is critical for successful implementation. By defining intended use cases and detailing methods, platforms, and associated costs, practitioners gain a clearer understanding of the financial implications of DT adoption. This work also aims to address one of the implementation barriers, the lack of standards, guides, common frameworks, and terminology, which often hinder widespread adoption. By tackling these challenges, the proposed framework strives to enhance feasibility and encourage broader industry adoption of DTs.

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APPENDIX A: EXAMPLE DT USE CASES

Table 5. A Representative Set of DT Use Cases (The full list of DT use cases can be accessed at https://www.cic.psu.edu/the-uses-of-digital-twins/)

Use Name	**to**	**Output - Digital**	**Output - Physical**	**Output - Human**	**Using**	**Method - Digital**	**Method - Physical**	**Reference**
Gather (Capture, Quantify, Locate)								
Capture bridge data		Create a machine learning (ML) model	-	-		-	Weigh-in motion sensors	(Adibfar and Costin, 2022)
Quantify CO_2 emissions		Analyze CO_2 emissions	-	-		-	CO_2 sensors	(Bjørnskov and Jradi, 2023)
Locate assets		Monitor assets	-	-		-	Sensors	(Song and Li, 2022)
Capture occupant data		Detect the number of occupants	-	-		-	Raspberry Camera and board	(Antonino et al, 2019)
Generate (Transform, Create)								
Create a prediction model		Predict CO_2 emissions	-	-		Environmental data	-	(Arsiwala et al, 2023)
Create a prediction model		Predict CO_2 emissions	-	-		Sensor data & ML algorithms	-	(Bjørnskov and Jradi, 2023)
Create a fault detection model		Detect faults	-	-		Images and ML algorithms	-	(Celik et al, 2023)
Analyze (Simulate, Classify, Detect, Validate)								
Analyze energy consumption		Optimize energy consumption	-	-		Sensor data	-	(Englezos et al, 2022)
Detect the number of occupants		Create a warning	-	-		Artificial intelligence (AI)	-	(Antonino et al, 2019)
Simulate CO_2 emissions		Optimize building performance	-	-		ML model	-	(Arsiwala et al, 2023)
Simulate energy consumption		-	-	Support decision making		Smart meter data	-	(Bayer and Pruckner, 2023)
Detect faults		-	-	Inform the users		ML model	-	(Celik et al, 2023)

Use Name	to	Output - Digital	Output - Physical	Output - Human	Using	Method - Digital	Method - Physical	Reference
Communicate (Visualize, Document, Interact, Inform)								
Visualize bridge data		Create a dashboard	-	-		Visualization APIs and bridge data	-	(Celik et al, 2023)
Visualize energy data		-	-	Support decision making		Visualization APIs and sensor data	-	(Dulaimi et al, 2022)
Document work orders		-	-	Communicate to user		Digital interface	-	(Ghorbani et al, 2024)
Interact with a digital dashboard		Create desired visualizations	-	-		Dashboard	-	(El Mokhtari et al, 2022)
Inform operators (of faults)		-	Fix the faults	-		Warnings in a dashboard	-	(Celik et al, 2023)
Realize (Actuate, Construct)								
Actuate a bridge		-	Fix the faults	-		-	Actuators	(Gao et al, 2023)