CSCE 2022 Annual Conference
Whistler, British Columbia
May 25th – 28th, 2022

Envisioning Digital Twin-Enabled Post Occupancy Evaluations for UVic Engineering Expansion Project

Tripathi, Ishan[1,4], Froese, Thomas[2] and Mallory-Hill, Shauna[3]
[1] MASc-Civil Engineering, University of Victoria, Canada
[2] Professor and Chair – Civil Engineering, University of Victoria, Canada
[3] Professor-School of Architecture, University of Manitoba, Canada
[4] itripathi@uvic.ca

Abstract: The University of Victoria is in the process of expanding its engineering and computer science department to meet the growing demand for post-graduate programs by building two new buildings. UVic's Green Civil Engineering department is actively involved in the project and planning to use the buildings as experimental apparatuses for various building science & systems research such as energy, water, indoor environmental quality, etc. These buildings aspire to achieve net zero carbon certifications to promote innovations in sustainability. Post-occupancy evaluations (POE) provide scientific methods and tools to analyze how buildings function and to quantify their performance. First, this paper establishes the semantics of POE in the context of the new engineering expansion project along with project phases. Second, this paper discusses the digital twin execution plan that can guide the evolution of digital twins during each phase of the project lifecycle for the purpose of POE. Third, this paper compares the proposed digital-twin-based POE methodology with the conventional POE methodology. Conducting the POE on the UVic ECS expansion project will enable the researchers to determine the effectiveness of sustainable features by comparing the performance of existing and proposed facilities.

Key Words: Post-Occupancy Evaluations, Digital Twins, IoT sensors

1 Introduction

The Civil Engineering department at the University of Victoria (UVic) aspires to be 'the greenest' department in Canada by focusing on sustainable technologies for design, construction, and management of the built environment without compromising the natural environment [1]. To meet the ongoing demand in education and research, UVic is in the process of expanding the current Engineering & Computer Science (ECS) building and building a new 'high-bay' intelligent research lab [2]. Aspirations for the proposed buildings are to achieve net zero carbon certifications. Moreover, the Civil Engineering department is getting involved throughout the project life cycle's planning, construction, and operations phases. This involvement aims to create a multi-disciplinary research platform that considers the buildings themselves as experimental apparatuses.

The design and construction of *high-performance* buildings have gained popularity during recent years [3]. However, only a few institutions worldwide are conducting building-scale research to evaluate the performance of in-use systems and capture complex interactions among buildings, people, energy systems & digital systems. UVic's Civil Engineering department is addressing this challenge by proposing to develop a digital twin for monitoring, optimizing, and managing physical systems. Moreover, questions such as *'How does the research on building performance shape future design?'* and *'Does constructing a sustainable* *facility really improve the footprint of the built environment?*' often arise during the planning phase of the project. Post-occupancy evaluations can be used to make data-oriented and structured arguments towards finding answers to these questions. Moreover, digital twins are becoming a standard norm for the Architecture, Engineering, Construction and Operations (AECO) industry for managing design, construction, and operations [4]. The digital twin applications can also be extended for collecting, analyzing, and managing data for POE [15].

This study aims to provide a high-level methodology for a digital-twin-enabled POE for UVic's ECS expansion project. A systematic approach for integrating the semantics of the POE framework with a digital twin execution plan to create the overall methodology has been explained further in this paper (section 4). Comparing this proposed methodology with a conventional methodology demonstrates the benefits of using digital twins for POE.

2 Points of Departure

2.1. Post Occupancy Evaluations

Post Occupancy Evaluations (POE) are a systematic approach to determine whether decisions made by designers, constructors, and facilities managers meet the building performance and end-user requirements. They offer a wide range of benefits that mainly align with obtaining design and operation feedback for future projects, operational improvements, and benchmarking for comparing performance within the same facilities [5]–[7].

Typically, POE are conducted after the building is occupied for at least two years. The data is collected for parameters such as energy, water, indoor environmental quality (IEQ), and occupant behavior towards the building performance. The collected data is then used to calculate key performance indicators (KPIs) [8].

The methodology for conducting POE varies according to purpose and type of projects [5], [7]. However, challenges such as time-consuming data collection, lack of provisions for using the building sensors' data, and inefficient visualization can be observed across the majority of the projects [9]. Integrating IoT-based sensors with a GIS-based Digital Twin can address those challenges by providing a centralized platform for data management, analysis, and visualization for POE [15].

2.2. Digital Twin ecosystem for Smart Building Research

The concept of a digital twin has evolved significantly during the past decade. There is no definitive definition of a digital twin. In the context of the Architecture, Engineering, Construction, and Operations (AECO) industry, a digital twin can be defined as a virtual replica of a physical asset [4]. Three key characteristics: representation of a physical building, bi-directional data exchange, and connection throughout the lifecycle of the building [10] have contributed to the paradigm shift towards the use of digital twins for the AECO industry. IoT-based sensors have become a backbone of the digital twins by facilitating dynamic data gathering and data exchange [4].

One of the objectives of UVic's research program is to use the digital twin for simulation and predictive analysis that can be used to monitor, control, and optimize physical systems. Researchers can develop deeper understandings by coupling living labs with digital twins [11]. There are examples of 'smart living labs' that facilitate interdisciplinary research through experiments in actual conditions. The Smart Campus Integration and Testing (SCIT) Lab at Ryerson University, Toronto, Canada, supports pilot-scale research projects that focus on building controls, operations, and occupants' behavior towards building performance [12].

Building Information Models (BIM) provide geometric and parametric information to digital twins. A BIM execution plan is a document that envisions and documents the implementation of BIM throughout a project's lifecycle. It usually contains the guidelines for developing people and processes, mobilizing existing and new technologies, enhancing efficiency through teamwork, and collaboration through common data environments [13]. In the context of the UVic ECS expansion project, the fundamentals of the BIM execution plan can be used to develop a 'digital twin execution plan' that will provide guidelines for building and using digital twins for POE.

3 Methods

This section explains the approach to creating a methodology for conducting performance evaluation on the ECS expansion projects by using a digital twin as a centralized platform for Data Acquisition, Management, Analysis, and Visualization. The Civil Engineering department at UVic proposes using digital twins for various research purposes. Moreover, the use of digital twins along with IoT sensors will enable dynamic data exchange between the physical building and its digital twin. Therefore, conducting POE can be considered as an extended use case of digital twins.

Figure 1 demonstrates the strategic approach considered for creating an overall framework that enables digital twins for POE.

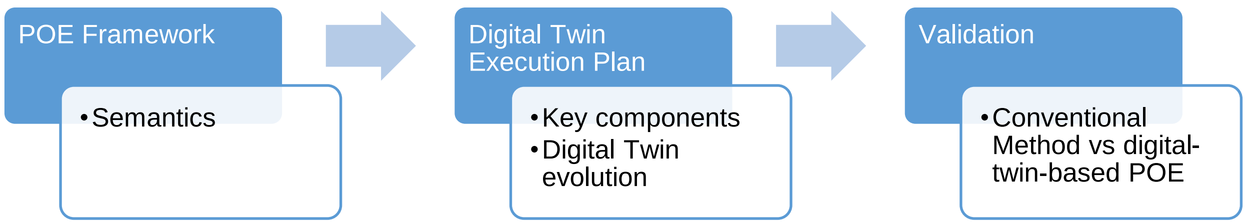

Figure 1: Strategic approach to creating a digital-twin-based POE methodology for UVic ECS expansion project

3.1. POE framework

The tools and techniques for conducting POE vary with the type of project and overall purpose [7]. Therefore, it is important to establish a high-level framework for POE that explicitly defines the semantics such as purpose, objective, scope, phases, frequency, and key performance indicators (KPIs).

3.2. Digital Twin Execution Plan

A Digital Twin Execution Plan uses the fundamentals of the BIM execution plan to provide a set of guidelines for developing a digital twin that accommodates the requirements of POE.

3.3. Validation

The recommended digital-twin-based POE methodology will be compared to the conventional method.

4 Discussions

4.1 Framework for Digital Twin based POE

This framework helps to establish semantics for conducting both *high-level* and *detailed* POE by using digital twins. It defines the goals, objectives, levels, frequency, and KPIs of POE for the UVic ECS expansion project.

4.1.1. Goals

- Determine the 'Performance Gap' by comparing the simulation data with actual data,

- Determine the effectiveness of sustainable features by demonstrating the reduction of environmental footprint, increase in positive impact, and improvement in occupant comfort.

4.1.2. Key Objectives

- To determine gaps in expected and actual performance,
- Determine the occupant comfort level within the building,
- Provide recommendations for improvement in operations,
- Provide design feedback for future purposes,
- Monitor real-time data and use it for the realistic calibration of a simulation model periodically for predictive analysis.

4.1.3. Scope

For this project, POE should be limited to research purposes by the Civil Engineering department only. Usually, digital twins are managed by the facilities management team along with Building Management Systems (BMS). Separating POE from the scope of the Facilities Management (FM) team is necessary for ensuring safety and privacy. However, further collaboration is encouraged through structured data sharing and decision-making.

4.1.4. Levels

Comparing the performance of existing facilities with the proposed new facilities is a standard way to prove the effectiveness of sustainable features. Therefore, POE can be classified into three levels.

Level 0: Pre-occupancy Evaluations (Pre-OE) on the existing ECS building.

Level 1: Preliminary POE on the expansion and the new high-bay structural lab.

Level 2: Detailed/Advanced evaluations if required after preliminary evaluations.

Level 0 and level 1 evaluations should be conducted for the same set of KPIs for accurate comparison between existing and new facilities.

4.1.5. Frequency of Evaluations

Traditionally, a preliminary POE is conducted after a minimum of 2 years of occupancy. However, with a paradigm shift from one-off to continuous, the frequency of evaluations should be decided prior to commencing as per the requirements set by the researchers and the facilities management team.

4.1.6. Key Performance Indicators (KPIs)

KPIs are useful to determine the effectiveness of parameters such as energy, water, Indoor Environmental Quality (IEQ), etc, that affect the sustainable performance of the building. Table 1 gives a brief overview of potential parameters that can be used to evaluate the sustainability goals of the UVic ECS expansion project.

The relevant research groups at UVic can expand upon these basic KPIs to develop more rigorous indicators for detailed investigations.

Table 1: An overview of potential KPIs for UVic ECS expansion project

Sustainability Goals	**Relevant Key Performance Indicators (KPIs)**
1. Reduce Carbon Emissions • Implementing sustainable transportation • Mass timber for reducing embodied emissions • Electric heat-pump for low carbon grid	• Materials & Waste during construction • Carbon accounting for transportation • Carbon accounting for electric grids
2. High Performance: Energy and IEQ • LED light fixtures • High-performance insulation • Optimized window to wall ratio • Exterior solar shading • Solar panels for generating electricity	• Energy use intensity • IEQ: Lighting, Acoustics, Temperature & Relative Humidity, Indoor Air Quality (CO2, CO, TVOC, particulates)
3. Sustainable Water • Low flow sanitary fixtures • Rain Gardens	• Water use intensity • Water uses by source • Water use by end-use • Rainwater harvesting
4. Biodiversity • Bird-friendly design • Green roof • Restorative landscape • Indigenous plantations	• Bio-Diversity Indicators
5. Occupant Health & Well-being	• Occupant Satisfaction • Impact of occupant behavior on building performance
6. Economic Factors	• Cost - feasibility of sustainable construction

4.2 Digital Twin execution plan for POE

4.2.1. Applications of Digital Twins for UVic ECS expansion

Determining potential applications of a digital twin during the planning phase is necessary for creating a digital twin execution plan for POE. The following are potential use cases for digital twins for the UVic ECS expansion project.

- <u>For research</u>: Simulations, predictive analysis, continuous monitoring, etc.
- <u>For facilities management</u>: Predictive Maintenance & Performance Evaluations
- Visualization and display of occupant comfort and satisfaction
- Public interaction and awareness & display of positive environmental impact
    - BIM model displayed on a screen near the entrance or anticipated ‘high traffic areas’ for demonstrating design features and showing the live KPIs for occupant comfort levels
    - For collecting feedback: at the end of the term, the occupant survey questionnaire can be distributed through UVic’s online systems for the students that used the building for a particular term.
- Gamification: for encouraging positive occupant behaviors towards building performance

4.2.2. Organizational Structure

- Based on the specialization of various research groups in the Civil Engineering department at UVic, having a separate digital twin is recommended for avoiding confusion and complications. Those digital twins should have dynamic data exchange connections with a federated digital twin (see figure 4).
- Each research group should nominate a representative for managing their respective digital twin. We recommend hiring a departmental coordinator to monitor the overall quality of the digital twin, verify the integrity of connections, and communicate with the facilities management team.

4.2.3. IT infrastructure

- **Hardware:** High-end graphics card for optimum performance, upgradable systems
- **Software**
  - Autodesk BIM suite for curating BIM models and collaboration
  - ArcGIS pro for integrating IoT sensors with BIM models and hosting digital twins. Its spatial-temporal analysis & visualization tools will potentially enhance the capabilities of digital twins.
- **Other:** Connection with local data repositories/ servers if applicable

4.2.4. Components of Digital Twins

I. Geometry

Curated BIM models provide necessary geometric information according to the desired level of details.

II. Sensors – Data types and networking

Sensors enable digital twin for continuous monitoring, effective visualization, and informed decision-making [4]. Table 2 gives an overview of the potential type of sensors that can be used within their respective systems according to their purpose.

Table 2: Potential type of sensors for UVic ECS expansion project

Purpose	Sensors	Related systems
Overall Building Performance	Thermal, Lighting, HVAC, Occupancy	Architectural, Mechanical, Electrical
Detailed Area Monitoring	Thermal, IEQ, Occupancy	Mechanical, Electrical
Water resources	Water flow, Water Use, Soil Moisture, Potable Water	Water
Building Envelope	Heat Flux, Temperature & Humidity, Green Roof	Mechanical, Electrical
Structural health monitoring	Moisture, Deflection, Vibration, Safety	Structural, Building Materials
Geo-technical monitoring	Settlement, Strain, Earth Pressure, Moisture	Geo-technical
Electrical	Usage, PV output	Electrical
Exposure to pollution	Mode of Transport, Occupancy	Outdoor Air Quality

III. Data connections

Connecting IoT-based sensors with the BIM model establishes a bi-directional communication between physical building and its digital twin. Figure 2 below demonstrates integrating sensors' data with the BIM model using ArcGIS Pro (hypothetical building and data are used here for visual demonstration only).

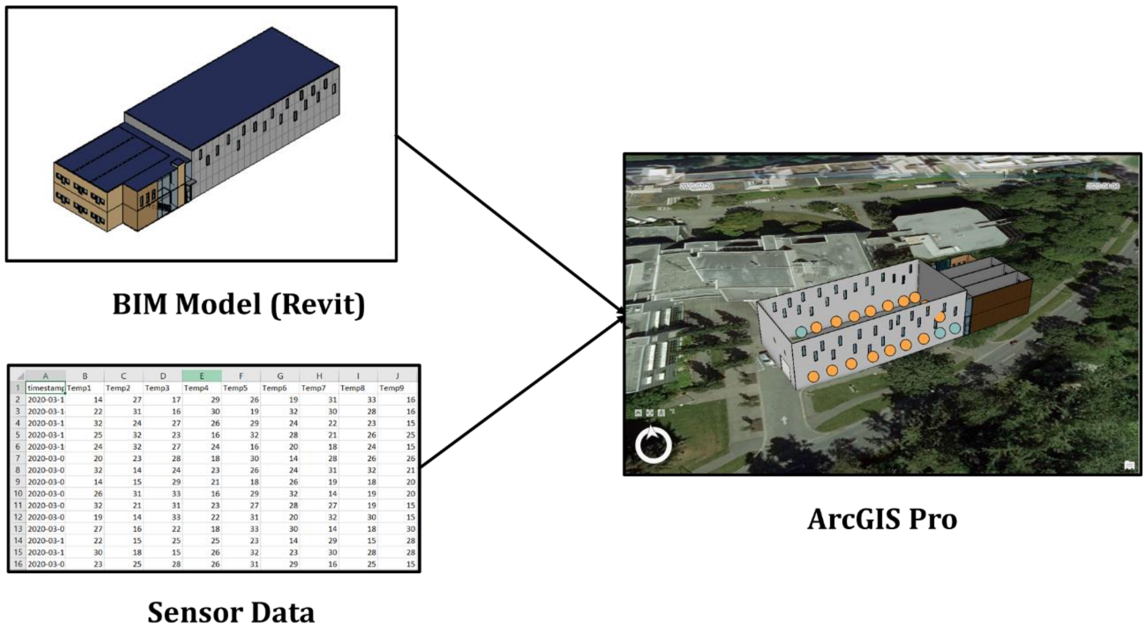

Figure 2: Example of connecting BIM model with sensors' data in ArcGIS Pro [15]

IV. Time: Refresh Rate

Setting refresh rate for sampling is vital for data collection and avoiding unnecessary clustering.

- **Sensors:** As per the requirements of the corresponding research group
- **Federated Digital Twin:** Federated model should be updated periodically; for example: once every term

4.2.5. Evolution of Digital Twins at each phase of the project

Figure 3 illustrates the tasks at each phase of the project life cycle that ultimately contributes to developing digital twins. For the purpose of POE, the commissioning phase is significant because it documents the initiation of different systems within the building, and its accurate documentation can be useful for re-calibrating the simulation model.

For the UVic ECS expansion project, a representative of each research group is required to create and update their version of the digital twin during the lifecycle.

As demonstrated in figure 4, key research areas for creating research-based digital twins are identified based on the research groups at the UVic Civil Engineering department. These research groups can manage their respective digital twins to avoid complications and privacy concerns. Moreover, a departmental representative should manage a federated digital twin that synchronizes the data from all research-based digital twins. The federated digital twin can be used to communicate with the facilities management team.

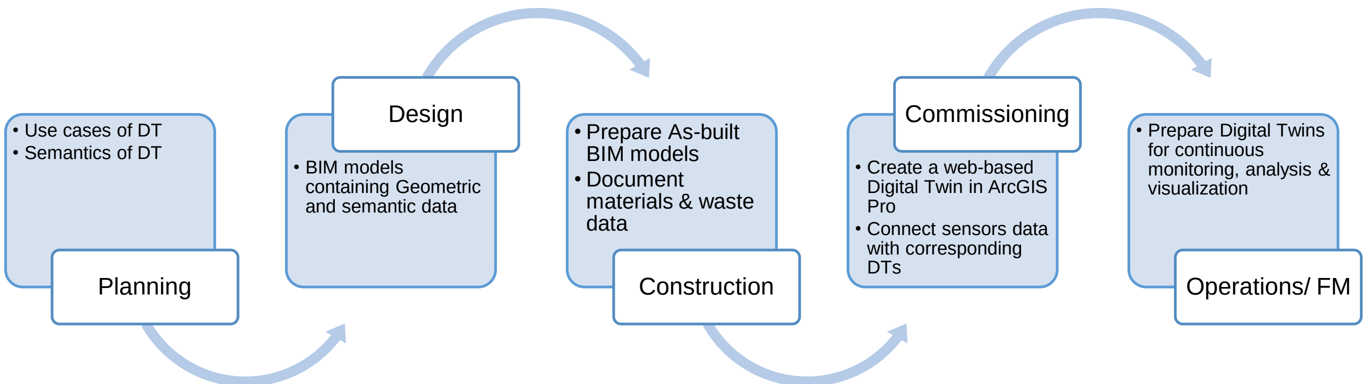

Figure 3: Evolution of Digital Twins

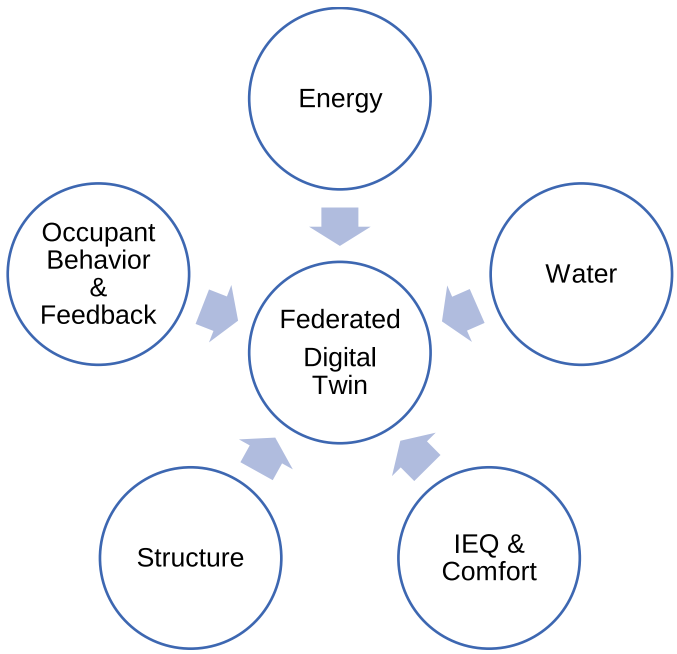

Figure 4: Conceptual illustration of a federated digital twin that is connected to various research-based digital twins

4.3 Challenges in implementation

- During the planning phase, collaborating with stakeholders such as constructors is challenging, especially for communicating the concept of POE.
- Separating research-based POE from the overall scope of facilities management while establishing an operational feedback loop parallelly.

- Occupancy sensors in an educational building are challenging due to privacy and security concerns and ethical reasons.
- Uploading the building models on ArcGIS Pro cloud-based servers would be difficult because of safety and intellectual property rights concerns.

5 Comparison

This section compares the conventional POE process with the proposed digital-twin-enabled POE process throughout the project life cycle.

Conventionally, facilities management commences during the *commissioning phase* (table 3), where the BMS sensors' database is created after different mechanical and electrical systems have been activated. Moreover, the entire procedure for conducting POE starts during the *operations phase* [14]. Evidently, this has resulted in time-consuming data collection methods and a lack of provisions for visualization for effective communication [9].

For the digital-twin-enabled POE process, relevant information can be added during each lifecycle phase. Moreover, digital twins use the 3D BIM model and integrated sensors' data for effective visualization. Furthermore, ArcGIS Pro enhances spatio-temporal analytical capabilities by providing GIS-enabled advanced tools [15]. By implementing machine learning, the proposed digital twin can provide intelligent insights into building performance.

Therefore, as described in table 3, integrating a POE framework with the digital twin evolution during the project life cycle improves the efficiency of data collection, analysis, and visualization of POE.

6 Conclusions

- Post Occupancy Evaluation will present an opportunity to the University to lead by example by demonstrating the effectiveness and positive environmental impacts of green buildings.
- Using digital twins will enable researchers to conduct detailed analyses within their respective research groups and collaborate with other research groups.
- Integrating the POE framework with the digital twin execution plan helps create a methodology for digital-twin-based POE. However, further discussion with all the stakeholders is required to optimize the methodology.
- Digital twins will facilitate the streamlining of POE and increase the efficiency of the overall methodology.

7 Next Steps

- Present this high-level digital twin enabled POE methodology to the Facilities Management team at UVic.
- Modify and detail the methodology as per the research and facilities management requirements
- Propose Pre-occupancy evaluations for the existing ECS and lab facilities used by the Civil Engineering department.

Acknowledgments

We would like to thank the Civil Engineering department at the University of Victoria for sharing their vision and information about the UVic ECS expansion project.

Table 3: Comparison between conventional and digital twin enabled POE processes

Project Phases	Conventional POE Process	Proposed Digital Twin Enabled POE Process
Planning		• Propose the extended application of Digital Twins for POE to the stakeholders • Establish semantics for POE & identify requirements of a Digital Twin platform for POE
Preliminary/ Schematic Design		• Propose the integration of IoT based sensor networks for continuous monitoring • Document the assumptions of Occupancy
Design Development		• Document values provided by the simulation model for relevant KPIs such as energy use, water use, lighting levels etc. • Start the development of a Digital Twin for extended FM/POE • Collaborate with designer for adding geo-location and built environment data
Construction		• Track and collect data for materials & waste • Track economic factors such as construction and commissioning costs for POE • Monitor the sustainable construction procedure where applicable • Update the Digital Twin using as-built model/ drawing
Commissioning	• Create a database for equipment and sensors for maintenance and FM	• Calibrate and connect the IoT based sensors' system and conduct preliminary monitoring tests • Add sensors' locations to Digital Twin and establish a data tunnel for connecting the physical sensors to their digital representation • Validate if the quality of the Digital Twin meets the requirements established during the Planning Phase
Operations/ FM	• Plan and conduct preliminary POE • Generate KPI report and identify gaps by comparing the values with design standards • Provide feedback for operations and design iteration	• Create a plan for periodic evaluations using IoT sensors' data • Conduct spot measurements if required and add them to relevant Digital Twins • Create a Digital Twin based feedback system for occupant surveys • Generate KPI report and compare it with the simulated values to identify gaps • Recalibrate the simulation model using sensors' data for future prediction

References

[1] “Green Civil Engineering - University of Victoria,” *UVic.ca*. https://www.uvic.ca/ecs/civil/home/green/index.php (accessed Feb. 21, 2022).

[2] “Engineering and Computer Science Expansion and New Lab Building - University of Victoria.” https://www.uvic.ca/campusplanning/current-projects/engineering-expansion/ (accessed Mar. 06, 2022).

[3] M. O’Mara, S. Bates, and L. Ap, “Why invest in high-performance green buildings?,” p. 24.

[4] buildingSMART international, “How to unlock economic, social, environmental and business value for the built asset industry,” 2020. [Online]. Available: https://www.buildingsmart.org/wp-content/uploads/2020/05/Enabling-Digital-Twins-Positioning-Paper-Final.pdf

[5] C. J. Roberts, D. J. Edwards, M. R. Hosseini, M. Mateo-Garcia, and D. G. Owusu-Manu, “Post-occupancy evaluation: a review of literature,” *Eng. Constr. Archit. Manag.*, vol. 26, no. 9, pp. 2084–2106, 2019, doi: 10.1108/ecam-09-2018-0390.

[6] S. Mallory-hill, W. F. E. Preiser, and C. Watson, *1 Introduction to Building Performance Evaluation: Milestones in Evolution*.

[7] P. Li, T. M. Froese, and G. Brager, “Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review,” *Build. Environ.*, vol. 133, pp. 187–202, Apr. 2018, doi: 10.1016/j.buildenv.2018.02.024.

[8] S. Mallory-Hill and M. Gorgolewski, “Mind the Gap: Studying Actual Versus Predicted Performance of Green Buildings in Canada,” in *Building Performance Evaluation*, W. F. E. Preiser, A. E. Hardy, and U. Schramm, Eds. Cham: Springer International Publishing, 2018, pp. 261–274. doi: 10.1007/978-3-319-56862-1_20.

[9] I. Tripathi and T. M. Froese, “Post Occupancy Evaluation in Canada: Challenges, Potential Improvements and New Frontiers,” 2020, Accessed: Jan. 30, 2022. [Online]. Available: https://dspace.library.uvic.ca/handle/1828/12338

[10] J. Trauer, S. Schweigert-Recksiek, C. Engel, K. Spreitzer, and M. Zimmermann, “WHAT IS A DIGITAL TWIN? – DEFINITIONS AND INSIGHTS FROM AN INDUSTRIAL CASE STUDY IN TECHNICAL PRODUCT DEVELOPMENT,” *Proc. Des. Soc. Des. Conf.*, vol. 1, pp. 757–766, May 2020, doi: 10.1017/dsd.2020.15.

[11] “Smart Living Lab.” https://www.smartlivinglab.ch/en/ (accessed Mar. 06, 2022).

[12] “WZMH’s Newest Project with Ryerson University will be the Smart Campus Integration and Testing Hub (SCITHub),” *WZMH Architects*, Aug. 26, 2021. https://www.wzmh.com/news/wzmhs-newest-project-with-ryerson-university-scithub (accessed Mar. 06, 2022).

[13] L. Joblot, T. Paviot, D. Deneux, and S. Lamouri, “Building Information Maturity Model specific to the renovation sector,” *Autom. Constr.*, vol. 101, pp. 140–159, May 2019, doi: 10.1016/j.autcon.2019.01.019.

[14] P. Pishdad-Bozorgi, X. Gao, C. Eastman, and A. P. Self, “Planning and developing facility management-enabled building information model (FM-enabled BIM),” *Autom. Constr.*, vol. 87, pp. 22–38, Mar. 2018, doi: 10.1016/j.autcon.2017.12.004.

[15] I.Tripathi, T. M. Froese, S. Mallory-Hill, “A BIM – IoT – GIS integrated Digital Twin for Post-Occupancy Evaluations”, *Unpublished Manuscript,* 2022