Conceptualizing the Next Generation of Post Occupancy Evaluations

by

Ishan M. Tripathi
B.Eng., Gujarat Technological University, 2016

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Supervisory Committee

Dr. Thomas Froese, Supervisor
Department of Civil Engineering

Dr. Shauna Mallory-Hill, Outside member
Department of Civil Engineering

Abstract

The design and construction of high-performance buildings have emerged as a preferred solution for reducing energy consumption and greenhouse gas emissions. However, sometimes there is a considerable gap between the design performance and the actual performance of the buildings. Post Occupancy Evaluations (POE) provide tools to quantify the performance relative to the occupant's health, well-being, and comfort. POE is getting widely accepted to obtain feedback for various parameters such as water, energy, indoor environmental quality, and occupant comfort. Key Performance Indicators (KPIs) can be derived based on the obtained feedback to determine the performance gaps. POE has evolved to be a robust scientific methodology; however, traditional methods of conducting POE have been proven time-consuming, inconsistent, and inefficient. This research aims to conceptualize the next generation of post occupancy evaluations that leverages cutting-edge technologies such as Building Information Modeling (BIM), Internet of Things based sensors (IoT), Geographic Information Systems (GIS), and digital twins. The key contributions of this research are presented in a series of manuscripts.

In the first paper, the gaps in the existing POE were determined by conducting a thorough literature review. The observed gaps were classified in data collection, analysis, and visualization categories. Broader POE definition, spot measurements of parameters, and 2D plans and charts for visualization made the existing POE procedure time-consuming. Using digital twins that combine the geometric and parametric data from BIM models and built-environment data from GIS and sensor measurements were recommended as potential solutions to address the observed gaps.

The second paper explored the application of BIM-IoT-GIS integration to conduct POE. Use case scenarios were developed to derive system requirements to host the BIM-IoT-GIS-integrated POE. Four sequential tests were conducted to integrate a BIM model from Revit and sensors' data from Excel with ArcGIS pro that contained the surrounding environment data. Based on lessons learned from the tests, an optimized workflow was recommended that can be used across a variety of projects.

The third paper used the BIM-IoT-GIS-integration concept to create a holistic proof of concept for digital-twin-enabled POE. The proof of concept was validated by conducting a digital-twin-based POE on the STTC building on the Red River College campus in Winnipeg. The indoor thermal comfort was visualized within the STTC digital twin developed in ArcGIS Pro. The preliminary energy consumption analysis concluded that the STTC buildings' average energy savings were approximately 70,000 KWH/year. The potential users for digital-twin-enabled POE were presented with a comparison of

existing POE and digital-twin-based POE over a survey and a focus group discussion. Based on opinion-based feedback, the conclusion can be made that digital twins improve the overall efficiency of POE.

The fourth paper recommended the digital-twin-enabled POE procedure for UVic's engineering expansion project. It established the semantics for POE, followed by a digital twin execution plan that can be used for developing a digital twin during each phase (from planning to operations) of the project. Furthermore, the benefits of the digital-twin-enabled POE procedure were demonstrated by comparison with the existing POE procedure relative to the project phases. This study concluded that 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.

In conclusion, BIM-IoT-GIS-integrated digital twins address the limitations of data collection, analysis, and visualization. These digital twins will enable multi-objective analysis and spatial-temporal visualization and provide deeper insights into the way these high-performance buildings function.

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I also acknowledge the arrangements made by the university staff amidst this pandemic that helped to continue my work.

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Thank you all!

Preface

This thesis presents the original and independent work of the author. It is based on a total of five published or under review manuscripts. Citations and author contribution details are as follows:

Paper 1

I.Tripathi, T. M. Froese, S. Mallory-Hill, “Next Generation of Post-Occupancy Evaluations: A summary of work”, NHICE-03, 2022 (Accepted)

- Parts of this manuscript form the basis for Chapter 1:.
- Tripathi summarized the research in a manuscript format. T. Froese supervised the research. T. Froese and S. Mallory-Hill revised the manuscript.

Paper 2

I.Tripathi and T. M. Froese, “Post Occupancy Evaluation in Canada: Challenges, Potential Improvements and New Frontiers,” NHICE-02, 2020, Accessed: Jan. 30, 2022. [Online]. Available: https://dspace.library.uvic.ca/handle/1828/12338

- This manuscript is presented in Chapter 2:.
- I.Tripathi conducted the Gap Analysis and wrote the manuscript. T.Froese supervised the project and revised the manuscript.

Paper 3

I.Tripathi, T. M. Froese, S. Mallory-Hill, “A BIM – IoT – GIS integrated Digital Twin for Post-Occupancy Evaluations”, Unpublished Manuscript, 2022 (Ready for submission)

- This manuscript is presented in Chapter 3:.
- I.Tripathi created use case scenarios, derived system requirements, prepared datasets, performed tests and validation for BIM-IoT-GIS integration, and derived the optimized workflow for BIM-IoT-GIS integration. T. Froese supervised the research. T. Froese and S. Mallory-Hill revised the manuscript.

Paper 4

I.Tripathi, T. M. Froese, S. Mallory-Hill, "Digital-twin-enabled Post Occupancy Evaluations: A proof of Concept", Unpublished Manuscript, 2022 (Ready for submission)

- This manuscript is presented in Chapter 4:.

- I.Tripathi created the proof of concept. Number Ten Architects provided the BIM model of the STTC building. The facilities management team at Red River College provided the raw sensors' data. For the case study, I.Tripathi prepared the BIM model, processed the data and performed calculations.

- The survey and focus group interview in chapter 4 is in the compliance with UVic's ethics approval, certificate number 21-0681

- I.Tripathi wrote the manuscript. T. Froese supervised the research. T. Froese and S. Mallory-Hill revised the manuscript.

Paper 5

I.Tripathi, T. M. Froese, S. Mallory-Hill, "Envisioning Digital Twin-Enabled Post Occupancy Evaluations for UVic Engineering Expansion Project", Unpublished Manuscript, CSCE 2022. (Under Review)

- This manuscript is presented in Chapter 5:.

- I.Tripathi created a digital twin integrated POE method and compared it with the traditional method. I. Tripathi wrote the manuscript. T. Froese supervised the research. T. Froese and S. Mallory-Hill revised the manuscript.

Chapter 1: Introduction

The Architecture, Engineering, Construction and Operations (AECO) industry is leveraging the innovations in sustainable technologies as solutions for reducing Green-House Gas (GHG) emissions without compromising living standards [1]. Following the global pandemic, people have realized the importance of Indoor Environment Quality (IEQ) for their health, safety, and well-being. Therefore, the demand for high-performance houses is increasing. However, the difference between the anticipated and the actual performance is often overlooked due to the lack of norms to evaluate these sustainable buildings. Therefore, investigating these 'performance gaps' will help obtain insights into the built environment and its impact on occupants [2].

Post Occupancy Evaluations (POE) provide scientific tools and methods for analyzing the built environment and assessing its performance [3]. It can be used to measure the performance of parameters such as energy, water and IEQ. Based on the collected data, Key Performance Indicators (KPIs) can be derived to understand the performance gap better and provide potential solutions. Methods for conducting POE vary according to purpose and type of projects [4]. Therefore, there is a need for a high-level framework that can be customized across various projects.

Building Information Modeling (BIM) models have the ability to provide detailed geometric and semantic information throughout the project lifecycle. Internet-of-Things (IoT)-based sensors offer cost-effective solutions for continuous monitoring of the built environment. Moreover, they establish seamless connections with other building management systems. Geographic Information Systems (GIS) have evolved to become powerful tools for analyzing and visualizing spatial-temporal information in the urban or rural built environment. Therefore, the integration of BIM-IoT-GIS presents a unique opportunity to host a centralized digital twin for POE [7].

1.1. Research Goal

The ultimate goal of this research is to create a proof of concept for the next generation of POE that can leverage the latest technologies such as BIM, IoT, GIS, and digital twins.

1.2. Research Objectives

The objectives of this research are as follows:

- To determine the current state of POE in Canada
- To find gaps in the existing POE methodology and propose potential solutions
- To develop use-case scenarios to derive system requirements
- To conduct experiments for integrating BIM, IoT, and GIS to create a digital twin
- To propose a proof of concept for digital twin-enabled POE
- To implement the proof of concept by conducting a case study
- To recommend a digital-twin-based POE methodology for a real-life project
- To compare the digital-twin-based POE with the traditional method

1.3. Thesis Structure: Reader's guide

Figure 1 illustrates a high-level research framework.

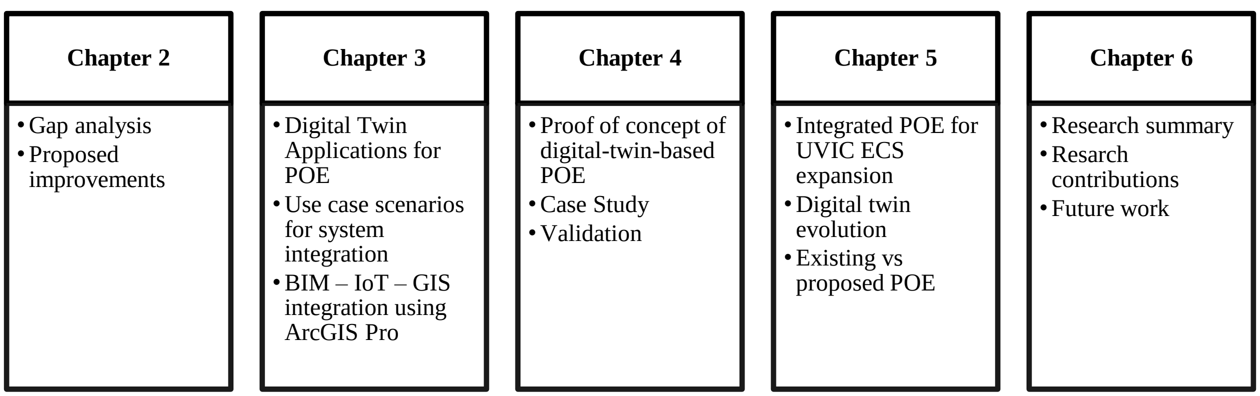


Figure 1: High-level research framework

- Chapter 2:, gap analysis, presents the current state of POE in Canada, observed gaps in existing POE methods, and potential solutions to address them. The use of BIM model with sensors' data is proposed as the potential solution to improve the overall efficiency of POE.

- Chapter 3:, digital twins for POE improvements, explains the integration of BIM, IoT, and GIS to develop a digital-twin-based methodology that addresses the existing gaps in POE.

- Chapter 4:, proof of concept for next generation of POE, uses the digital-twin-based methodology to create the proof of concept. The study attempts to validate the proof of concept by using real data associated with STTC building at Red River College. Furthermore, it demonstrates the effectiveness of 3D visualization for POE by summarizing the opinion-based survey conducted among academic researchers and discussions with professionals.

- Chapter 5:, application of the proof of concept, recommends a methodology for conducting digital-twin-based POE for the UVic's new ECS expansion.

Chapter 2: Post Occupancy Evaluation in Canada: Challenges, Potential Improvements and New Frontiers

I.Tripathi and T.M.Froese, "Post Occupancy Evaluation in Canada: Challenges, Potential Improvements and New Frontiers", NHICE 02, 2020.

2.1. Abstract

Canada's Build Smart strategy[5] has a goal to build high-performance buildings by integrating occupant comfort with energy efficiency. Despite having established best practices to design high-performance buildings, there is a considerable gap between sustainable design and the actual performance of the building. Building performance evaluation provides tools and methods to investigate and analyze performance gaps in the buildings. Pre-occupancy and post-occupancy evaluations can be used to assess the way building's function and establish a better understanding of sustainable performance. First, this study discusses the background and evolution of post-occupancy evaluation techniques in Canada. Second, the paper summarizes the methods and findings of a 2014 study by the International Institute of Sustainable Built Environment Canada that conducted post-occupancy evaluations of several green buildings across Canada, and it identifies the limitations of this study's protocol. Third, the paper discusses potential improvements to refine and prepare the protocol for a new iteration of studies in 2020, including foundations for a more rigorous and specific level of post-occupancy evaluations.

2.2. Introduction

The building sector accounted for almost 1/3 of the total energy consumption and Green House Gas (GHG) emissions in Canada in 2016 according to a Natural Resources of Canada's survey [4]. Moreover, according to the World Green Building Council's report in 2015, people spend a significant amount of time indoors (almost 90%). Therefore, indoor environment plays a vital role in occupants' health, well-being and productivity [4].

Efforts to address buildings' impact on the environment while still addressing the occupants' experience have inspired several sustainable agendas and policies in Canada such as the Energy Step Code in British Columbia and the Build Smart strategy at the federal level. Despite these initiatives, there are a lack of norms in evaluating these green building relative to their expected performance criteria. When these evaluations are conducted, there are often gaps between the expected and actual performance

[6], which is regarded as ‘the performance gap’ in the industry. Therefore, there is a need to measure the performance of the buildings after they are occupied to understand the performance of the implemented strategies, to investigate the performance decay over time and to inform decision making to improve facilities management.

Building Performance Evaluation (BPE) is a systematic and rigorous approach encompassing a number of activities including research, measurement, comparison, evaluation, and feedback that take place through every phase of a building’s lifecycle, including: planning, briefing/programming, design, construction, occupancy and recycling [6]. Apart from the technical aspects, it also helps to establish the effects of human behaviour, needs and desires.

Post-Occupancy Evaluation (POE) is a part of BPE that can be used to obtain feedback about various parameters such as energy performance, indoor environmental quality (IEQ), occupant satisfaction, productivity, etc. [4]. Based on the collected data, Key Performance Indicators (KPIs) can be derived to establish a better understanding of the performance gap and to provide potential solutions.

The primary aim of this paper is to determine the current state of and potential improvements for POE in Canada. First, the paper provides background of POE and discussion the findings from a 2014 POE study by the International Institute of Sustainable Built Environment Canada (iiSBE). Second, the discussion section describes the POE protocol developed by iiSBE. Third, the limitations of the 2014 iiSBE protocol are discussed. Fourth, potential improvements and suggestions are proposed for a new series of POE studies that iiSBE is planning to conduct in 2020.

2.3. Points of Departure

This section summarizes reviews of POE by Li et al. [4] and Mallory-Hill et al. [6], [3].

2.3.1. The Background and Evolution of POE

The roots of POE date to the 1960s. Since then, POE has evolved to include a variety of practices. Simultaneously, the building sector’s shift towards achieving energy efficiency and minimal environmental impact has driven the industry towards the adoption of the green certification systems [2]. There are at least 150 different green certifications around the world such as LEED, Green Globe, ASHRAE etc. However, their ability to provide the expected performance is comprehensively debated in the literature.

Li et al. [4] argues that even though POE is gaining popularity, it is still an underdeveloped concept. The analysis of 146 POE studies in the paper concludes that residential buildings are the primary research targets, and occupant comfort is the most common focus among all the studies, which results in occupant surveys being the most frequently used method. Ultimately the paper gives five topics as a future direction of POE: from one-off to continuing, from high-level to detailed, from researchers-oriented to owners/occupants oriented, from academia to industry, and from independent to integrated.

The nature of POE studies varies according to their purpose. Also, it is difficult to link POE studies back to original root causes and project phases [6]. Despite decent efforts from the industry, POE studies are difficult to generalize, which makes standardizing POE protocol a challenge [4].

2.3.2. POE in Canada – iiSBE Studies 2014

The 2014 iiSBE study was initiated as a Canada-wide study of a total 9 different green buildings across different regions. The main objective of the study was to create a standardized POE protocol suited to the Canadian Industry. Despite the limitations, the team was successful in identifying crucial performance gaps in all nine buildings. Analyses of these gaps helped the team conclude key issues, potential areas of improvement in design, construction, commissioning & operations phases, and evolution of POE as a process. Below are the key takeaways from the 2014 iiSBE POE study [3].

- More emphasis on communication and commissioning stage rather than primarily on the design stage.
- Benchmarking is difficult except for energy.
- Without recalibrated models, it is difficult to determine the performance gap
- Commissioning is often overlooked and should be one of the key processes for improving the performance.
- Without submetering, collecting desired data is challenging.
- Three building underperformed in the modeled and actual energy performance. Some of the factors are inconsistency in occupancy modeling, unregulated occupant behaviour and lack of building systems commissioning.

- Water use is depended on the occupancy.

2.4. Methodology

A literature review has been conducted to identify the BPE & POE concepts. Moreover, a thorough study of the 2014 iiSBE project is conducted to describe the findings and limitations of the project. These findings have been used as a base to suggest improvement and to determine next steps for POE in Canada. Also, these suggestions will be used as a part of the second iteration of iiSBE project in 2020.

2.5. Discussions

2.5.1. POE - Concepts and Definitions

POE has a very wide range of definitions and scope according to various literature [4]. Pre-Occupancy Evaluations (Pre-OE) and Post-Occupancy Evaluations (POE) forms a part of systematic BPE approach. In this section, concepts of Pre-OE and POE in the context of the iiSBE Canada project have been summarized.

- Post-Occupancy Evaluation (POE)

POE is a process of evaluating building performance after it has been occupied for at least 2 years. It is usually a measure of how well the design objectives are met without compromising the occupant comfort [3].

- Pre-Occupancy Evaluation (Pre-OE)

Pre-OE evaluates the existing building before retrofits and addition of green features. Moreover, it can be used to assess the current conditions of occupants who will occupy a greener building. It uses techniques that are similar to POE [3].

2.5.2. The 2014 iiSBE Protocol

The protocol formed by iiSBE was intended to help standardize the gathering and processing of information for the KPIs.

The protocol's objective is to use a series of indicators to compare simulated performance at the design stage with actual performance achieved after at least 2 years of occupancy. Moreover, it can also be used to provide reference values for typical performance for similar buildings in the same region.

Below are the KPIs chosen by the iiSBE 2014 research team for the assessment of nine buildings across Canada.

- Energy
- Water
- Materials & Waste
- Indoor Environmental Quality
  - Lighting
  - Thermal Comfort
  - Acoustics
  - Co2
  - Particulates
  - Total Volatile Organic Compounds
- Economic Factors
- Occupancy Factors

2.5.3. Methodology

- Onsite building observation,
- Collection of design documentation regarding building type, spatial allocation, floor plans, green building rating systems, etc.,

- Collection of metered data for water and energy use,
- Spot measurements for IEQ with the use of an IEQ measurement cart,
- A standard survey of occupant comfort,
- Interview with design team, building owner/manager and when possible, occupants,
- Data Analysis & KPI determination, and
- Findings & Conclusion.

2.5.4. Challenges in the 2014 iiSBE Protocol

Observed limitations in the 2014 iiSBE protocol are as follows:

- The definition of the performance gap is very holistic.
- Data collection and management procedures need to be more structured.
- There needs to be a standardized benchmarking for equipment used for spot measurement and its data collection.
- New buildings have started to integrate sensors as a part of Building Management Systems (BMS), however, there are no provisions regarding using BMS data along with spot measurements.
- There is not an efficient way to measure occupancy with high accuracy.
- Better visualization required to communicate the performance gap at a non-technical level.

2.5.5. Proposed Improvements in the iiSBE Protocol

Based on the literature review and identified gaps, potential improvements are proposed to generalize the POE process and make it more robust.

- Levels of Evaluations

The BPE process should be divided in three levels for better data collection and analysis purposes.

  - Level 0: Pre-Occupancy Evaluations

  Evaluations for existing buildings using the same KPIs from the 2014 iiSBE protocol.

  - Level 1: Post Occupancy Evaluations

  Preliminary evaluations using the 2014 iiSBE protocol after the new green building has been occupied for at least 2 years.

  - Level 2: Post Occupancy Evaluations

  Detailed Investigation after conducting preliminary Level 1 evaluations.

- Data Collection & Management
  - Standardize the equipment with specifications and tolerance for consistency,
  - Integration of the data from BMS systems and other sensors along with the spot measurements,
  - Pilot and implement efficient ways for occupancy tracking,
  - Cloud-based and structured database for the effective data management and collaboration, and
  - An interactive occupant survey to encourage more engagement.
- Data Analyses and Visualization
  - Visualization of POE through Building Information Models (BIM)
  - Graphical demonstration of occupant comfort levels within their space of use for intuitive communication.

- Analyses of the occupant survey databases is a very crucial topic and subjected to further research

2.6. Next Steps

- Revisit and refine level 1 iiSBE protocol that was developed in 2014.

- POE studies will be conducted on several new green buildings across Canada in 2020 (these studies did not take place due to the COVID 19 pandemic).

- An attempt will be made for visualizing POE and occupant comfort data through BIM models.

2.7. Conclusions

- POE is a vital component of the design – construction – operations life cycles of the building. Although, it's still underdeveloped in Canada, it should be integrated as a part of sustainable agendas and green building certifications.

- Due to the unique nature of POE studies, it is difficult to generalize the protocol, however, it is possible to develop a protocol that can be easily customized according to the nature and location of the building and purpose of POE.

- Despite of the limitations, the 2014 iiSBE protocol lays a solid foundation for 2020 POE studies.

- The current iiSBE protocol can be improved by linking sensors with data collection, utilizing cloud-based technologies for better organization and collaboration, efficient occupancy tracking and effective visualization of spatial comfort and performance gaps through BIM.

Chapter 3: A BIM – IoT – GIS integrated Digital Twin for Post-Occupancy Evaluations

I.Tripathi, T. M. Froese, S. Mallory-Hill, "A BIM – IoT – GIS integrated Digital twin for Post-Occupancy Evaluations", Unpublished Manuscript, 2022

3.1. Abstract

Post Occupancy Evaluations (POE) provide a systematic methodology for determining the performance gap between expected and actual performance. Monitoring quality of the indoor environment is essential for understanding building performance in relation to occupant health, wellbeing, and comfort. Technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and Geographical Information Systems (GIS) have the potential to address existing challenges for data collection, analysis, and visualization in POE. This study aims to explore the applications of a BIM-IoT-GIS-integrated Digital twin for POE. First, high-level use case scenarios are developed to derive system requirements for a Digital twin platform. Second, four tests are conducted that provide a step-by-step procedure for BIM-IoT-GIS integration. Third, the integration is validated by geo-reference checks, data transfer checks, and visual checks. Based on the tests, a streamlined workflow is recommended for similar/future projects. The results demonstrate that Revit-ArcGIS Pro integration meets the system requirements for POE. Moreover, as shown in the graphical abstract (Figure 2), the spatial-temporal capabilities of ArcGIS Pro enable continuous monitoring and visualization of building performance in 4D. In conclusion, BIM-IoT-GIS integration can provide a solid foundation for developing a centralized digital twin for POE.

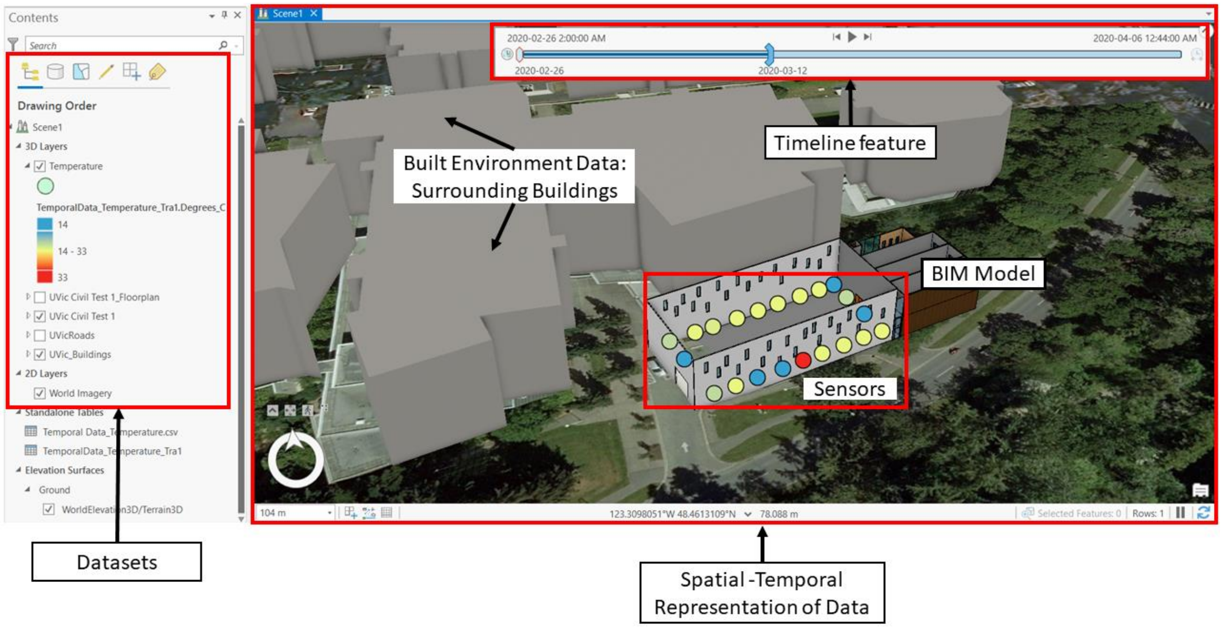


Figure 2: The integration of BIM model (Revit) and sensors' data (Excel) with ArcGIS Pro

3.2. Introduction

Standards and certification systems such as LEED, Green Globe, WELL, Passive House & Living Building challenge have inspired designers to incorporate innovative solutions and newer technologies in the built environment. Green buildings are expected to reduce energy consumption and Greenhouse gas (GHGs) emissions while improving the quality of the built environment [4], [6], [7]. People spend the majority of their time indoors. The Indoor Environment Quality (IEQ) impacts occupants' health, wellbeing, and productivity [4], [8]. Moreover, IEQ provides an insight into building performance in relation to occupant comfort and satisfaction [9]. These considerations—energy consumption, GHG emissions, IEQ—and many others- make up a building's overall performance.

To determine the gaps between the design and the expected overall performance of a building, POE have gained more significance [10]. Current methods of capturing performance data for key performance indicators (KPIs) such as water use, energy use, and IEQ factors: lighting, acoustics, temperature & humidity, air quality, etc., are not sufficient for determining spatial-temporal variations [9]. For example, the indoor thermal comfort data is captured manually and presented in 2D graphs, making it difficult to associate with the space directly. The challenges of similar nature can be observed for other KPIs as well. Therefore, a paradigm shift from independent to continuous evaluations is required to improve the overall efficiency of POE. These continuous evaluations will enable the analysts to accumulate and visualize data relative to the space over the desired time. Furthermore, continuous monitoring of the built environment will capture detailed information about changes that may get overlooked during just high-level assessments [4].

IoT-based sensors offer cost-effective solutions for continuous monitoring of the built environment. BIM applications are evolving to accommodate the post-construction phases such as commissioning, operations, and facilities management [11]. In parallel, GIS has evolved to become a robust science for analyzing and visualizing spatial-temporal information in urban & rural systems as well as the built environment [12]. Taking advantage of the strengths of each of these evolving technologies, integrating BIM & IoT data with a GIS environment provides a solid foundation for creating a virtual version of the physical asset–commonly referred as a 'digital twin' in the Architecture, Engineering & Construction (AEC) industry. Using digital twins for POE will not only address the ongoing challenges in data collection, analysis & visualization to improve the overall efficiency [3], [4], [7] but also drive the transition towards continuous and detailed evaluations.

This research explores the use of BIM-IoT-GIS integrated digital twin for POE. Section 3.2 highlights the need of digital twins for continuous monitoring and detailed analysis of the built environment. Section3.3 defines key concepts in the context of this research and provides a review of related literature and similar studies. The core contribution of this research is presented in two main phases. Section 3.4 gives an overview of the methods used for both phases: deriving system requirements for POE and tests conducted for BIM-IOT-GIS integration. Section 3.5 discusses the use cases developed for deriving system requirements. Section 3.6 and 3.7 demonstrate a step-by-step procedure for BIM-GIS integration and validation. Section 3.8 recommends a streamlined BIM-IoT-GIS integration workflow for similar projects and section 3.9 discusses the limitations.

3.3. Literature Review

3.3.1. Summary of key concepts

- Facility management (FM)

Facilities management generally refers to the management of built facilities during their operational phases, including tasks such as maintenance, repair, and renovation. As described by the International Facility Management Association, *'Facility management (FM) is a profession that encompasses multiple disciplines to ensure functionality, comfort, safety, and efficiency of the built environment by integrating people, place, process, and technology.'* [13]

- Post-occupancy evaluations (POE)

POE is a scientific method used for obtaining feedback about various parameters such as energy use, water use, IEQ, and occupant behaviour that influence the building performance [4], [14]. The obtained data can be used to calculate KPIs to determine the differences between the designed and actual performance of the buildings.

- Internet of Things (IoT)

IoT refers to the network of interconnected sensors and software designed to communicate with other devices and people over the internet [15]. They offer cost-effective solutions for continuous monitoring of the built environment [16]. IoT sensors are extensively used in the FM industry for predictive maintenance analysis of various assets [17].

- Building Information Modeling (BIM)

BIM can be summarized as a system of creating, sharing, exchanging, and managing information among the stakeholder throughout the project lifecycle [12]. With the range of applications from design coordination to facilities management, BIM is leading the digital transformation of the AEC industry. As more information is added during each phase of the building lifecycle, the BIM model evolves from containing geometrical information to a data-rich model that can be used as a data source for developing the digital twin [18].

- Digital Twin

The digital twin can be defined as a digital representation of a physical asset. The physical asset and its digital twin are linked and constantly exchange data in real-time throughout the Plan – Build – Operate & Integrate of the lifecycle. Technologies such as IoT enable dynamic data gathering and exchange [19].

- Geographic Information System (GIS)

GIS is a system to collect, manage, modify and analyze geographical data [20]. GIS can provide information about the built environment, such as weather and surroundings. [21]. It facilitates spatial-temporal data analysis in a 3D environment along with the management of large datasets.

3.3.2. Project Dasher 360

Figure 3: Project Dasher 360 User Interface [22]

Project Dasher is a multi-disciplinary research project conducted by Autodesk, and—as a tool that has been used for several research projects but is no currently available as commercial software—it is an example of the current state-of-the art in representing building performance data in a digital twin-type of format. It features a BIM-based platform created with APIs from Autodesk Forge that enables real-time visualization of building performance [22]. Figure 3 demonstrates the user interface of Dasher 360. Moreover, it has a time-liner feature for visualizing time-series data. Intuitive navigation features and enabling/disabling layers make the web-based model easier to operate. However, it does not feature any provisions for integrating the surrounding environment data. Also, integrating multiple BIM models over a large geographical area in the same interface would be challenging.

3.3.3. Interoperability between BIM and GIS

The main purpose of combining BIM with GIS is to integrate strong components of both systems for creating a data-rich virtual model of assets within the built environment [12]. BIM provides detailed information about the geometry, materials, and other parameters of the asset. GIS provides spatial information that can be used for in-depth analysis of the built environment. BIM is widely used for improving efficiency in design coordination and construction management. GIS has evolved into a robust system that supports spatial-temporal analysis and visualization of data sets for large-scale urban environments. Both BIM and GIS have tools and procedures for visualizing data in 3D environment. Considering BIM can add detailed semantic information to GIS, and GIS provides geospatial context to BIM models, integrating BIM-GIS has great potential for facilities management by providing spatial-temporal analysis and management tools[12], [23].

BIM and GIS can be integrated at the data layer and the application layer. Data layer usually refers to the transfer of geometric & semantic information between the platforms, whereas the application layer extends the scope of both BIM and GIS by enhancing each of their capabilities [24]. BIM models can be automatically geo-referenced with appropriate GIS integration [25]. Geo-referenced BIM models can then be imported into GIS with added built environment data such as surroundings, terrain, and weather [24]. The open-source BIM file format IFC is most frequently used in previous studies for importing BIM models into GIS [21], [24], [26], [27]. Minor discrepancies related to data loss have been documented during the conversion from IFC file format to Multi-patch shapefiles [26], [27].

The tools for BIM-GIS integration are constantly evolving over the past few years with the increase in the number of studies exploring the applications of this topic [12]. Indoor data mapping with BIM-GIS integration improves navigation in a complex environment [28] and can be used for indoor mobility analysis [29], and evacuation planning for emergency response [30], [31]. Moreover, the indoor mapping feature of BIM-GIS is useful for collecting data for assessing the impact of human behavior on building performance, which is a known challenge in previous POE studies [32]. Facilities management is the longest phase of a construction life cycle where applications of BIM-GIS integration can be used to manage large datasets. In the context of POE, a BIM-IOT-GIS integrated digital twin can be developed for continuous monitoring and visualization of building performance.

3.4. Methods

This section explains the methodology for combining BIM and GIS to create a digital twin that integrates data collected by building performance monitoring sensors. The GIS integrated digital twin facilitates the visual representation of continuous monitoring within the corresponding 3D space in the BIM model.

The key contributions of this paper are presented in two phases. Phase 1 represents the use case scenarios developed for capturing the system requirements to create a digital twin for POE. Phase 2 represents the actual step-by-step tests conducted for integrating the BIM model and sensors' data into GIS. Findings from Phase 2 are summarized and converted into a workflow that can be replicated for future projects.

3.4.1. Phase 1: System Requirements for POE

Use case scenarios created with the Unified Modeling Language (UML) are a proven approach for capturing system requirements [33]. They are made of simple diagrams and texts that describe the interactions of users and external factors with the system for carrying out specific tasks [34]. For this research, use cases scenarios are developed to depict high-level activities to be performed by potential users in a system that incorporates a digital twin for POE. Then, the use cases are used to derive specific requirements for a system that can host a digital twin that can integrate BIM, GIS, and sensors' data.

3.4.2. Phase 2: BIM – IOT – GIS integration

- Tests

The tests are designed to represent the tasks to be conducted by potential users of BIM-GIS integration for POE-related activities. They provide a systematic procedure for integrating BIM and sensors' data with the GIS ecosystem.

- Validation

A geo-referenced BIM model is the foundation of a GIS integrated digital twin. As summarized in the literature review section, loss of data during integration is one of the main challenges of BIM-GIS interoperability. There are no established methods for the validation of BIM-GIS integration. Moreover, the BIM-GIS integration should meet the system requirements for POE. The Table 1 describes the three types of checks used for this study.

Table 1: Validation of BIM-GIS integration

No.	**Validation Type**	**Purpose**
1	Geo-reference checks	To verify if the BIM model and sensors' data have been geo-referenced correctly and imported to the correct location in the GIS environment
2	Data transfer checks	To verify the accuracy of data transferred from the BIM model and sensors' data
3	Visual checks	To verify the import of visual components such as geometries, materials, textures, etc.

3.5. Phase 1: System Requirements for POE

A digital twin platform that integrates the BIM model, IoT sensors' data, and GIS will improve the overall efficiency of POE [7]. The focus of this integration targets three applications that improve the data collection, management, data analysis, and data visualization for POE. Figure 4 describes the potential applications of this integration.

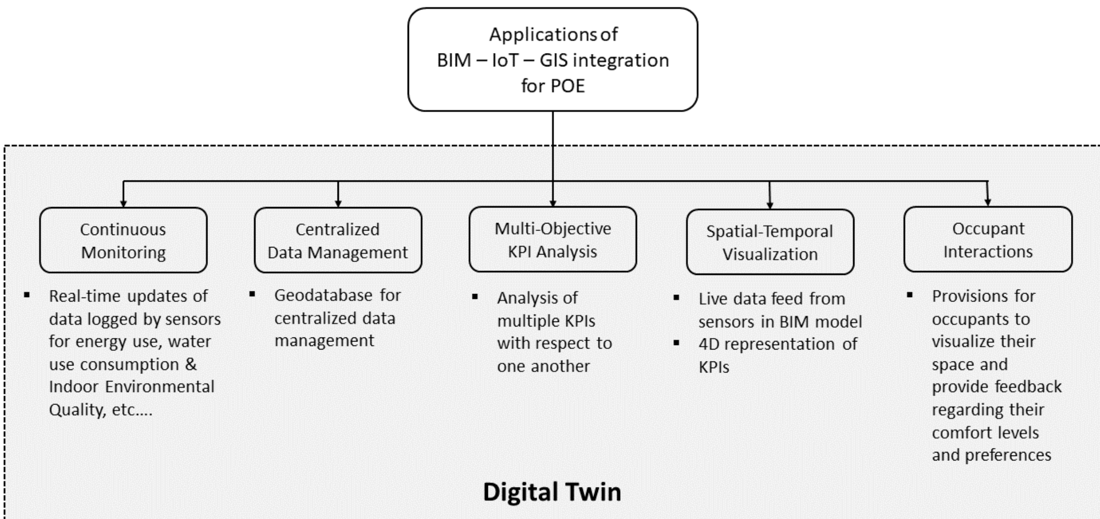


Figure 4: Applications of BIM-IOT-GIS integration for POE

IoT-based sensors for monitoring building performance constantly collect data about KPIs such as energy use, water use, and indoor environmental quality. Spatial and temporal analysis tools in GIS can use geometric data extracted from BIM models and sensors' data to calculate the values for KPIs. A geo-referenced BIM model located in the built environment incorporating real-time sensors' data creates a 4D spatial-temporal visualization that can be used for preliminary analysis and decision-making. Spatial-temporal analysis and visualization enable the possibilities of multi-objective analysis where multiple parameters or calculated KPIs can be visualized relative to one another. With the muti-objective analysis, visible co-relations among multiple KPIs can be established.

For example, visualizing weather data, indoor thermostat data, building façade data for R values, natural lighting, and roof monitoring can help researchers establish a correlation between the impact of the indoor and the outdoor environment on the environment energy expenditure with relation to occupant comfort. The potential of such digital twins can exceed the typical applications of digital twins, POE and FM.

3.5.1. Use Case Scenarios for POE

This section presents four high-level use case scenarios for creating a digital twin using BIM-GIS integration for POE. Scenarios 1,2, and 3 illustrate the individual tasks to be performed by potential users. Scenario 4 is developed to demonstrate an application that involves the interaction of potential users and external datasets with the system.

- System Users

The operations/ FM phase is the longest phase of a building life cycle. Facility managers and building operators often make decisions about the building operations. Also, occupant behaviour has an influence on building performance. The majority of the POE studies have been conducted by academic researchers. Therefore, the potential users of the digital twin for POE are enlisted below:

  - Facility Managers/ Building Operators
  - POE Analysts (Academic Researchers and/or Industry Professionals)
  - Occupants

- <u>Scenario 1: Data Integration for Building Operations/ Facilities Management</u>

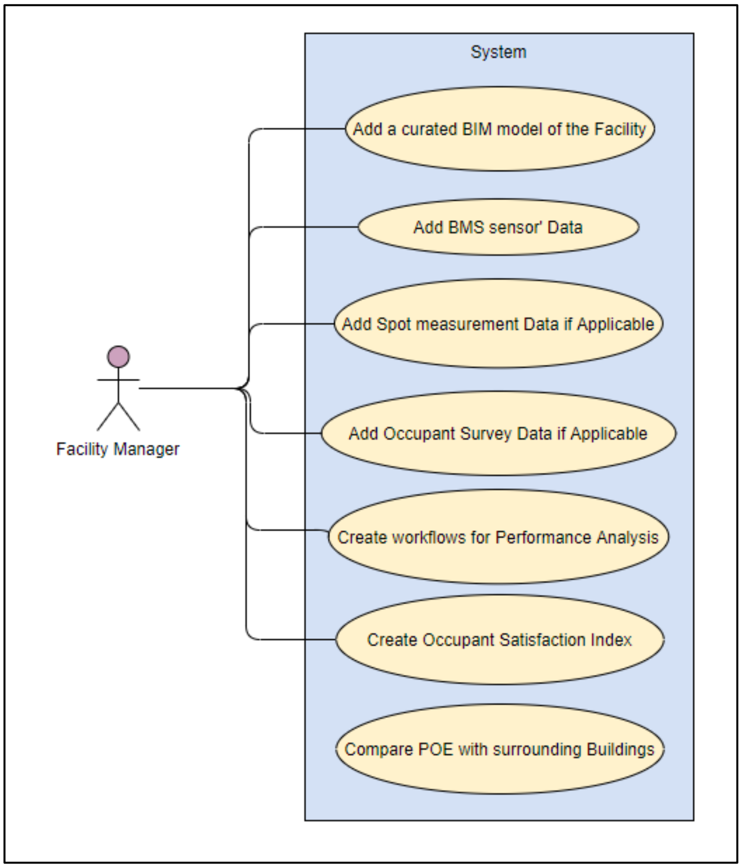


Figure 5: Use case for the facility manager

In the first use case (Figure 5), the facility manager and/or building operator initiates the process by linking sensors' data, spot measurements, and occupant survey responses with the curated BIM model of the facility. The integrated data creates a virtual representation of the physical building. These datasets are used for creating workflows for performance analysis and visualization. The results are used to create an index that shows occupant satisfaction within the built environment. If there are multiple facilities involved, this scenario also extends to comparing the performance of similar facilities for various purposes of POE.

- <u>Scenario 2: Data Analysis for POE</u>

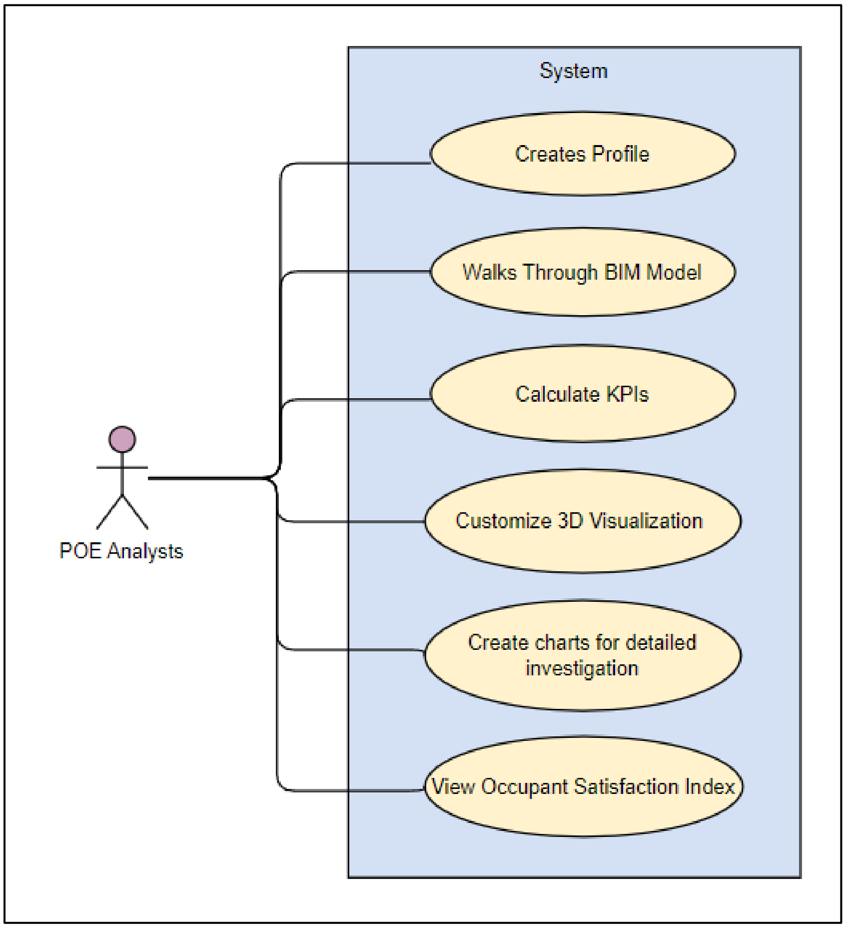


Figure 6: Use case for POE analysts

In the second use case (Figure 6), analysts create their own profiles to view the digital twin. They can navigate the BIM model and visualize the sensors' data easily. Moreover, they have the option to perform in-depth analysis. They can also create custom visualization and produce different charts. The results are used to communicate the findings and make decisions for operational changes and/or retrofits. However, they do not have access to editing the data entered by the facility manager.

- <u>Scenario 3: Occupant feedbacks for comfort levels</u>

In the third use case (Figure 7), the occupants are given access to walk through the BIM model. They can navigate to their corresponding areas to visualize the KPIs. Furthermore, they have the option to provide feedback through survey forms that are used to create the occupant satisfaction index.

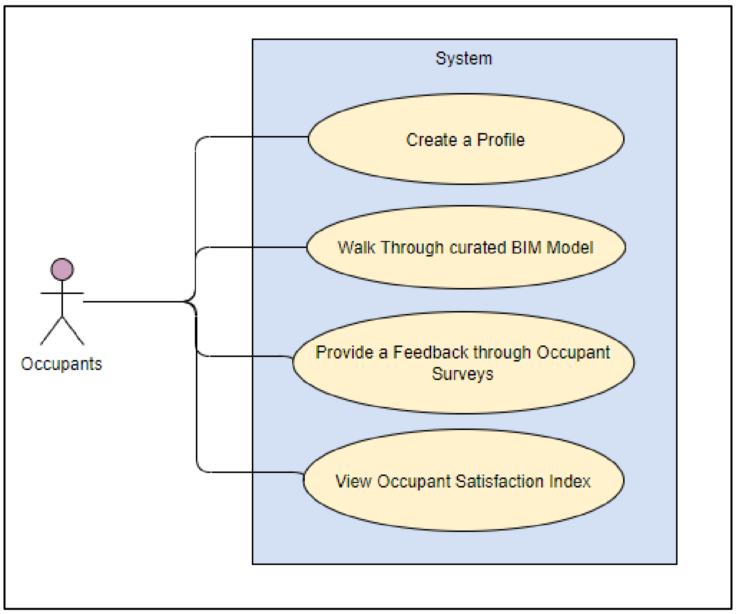


Figure 7: Use Case for occupants

- <u>Scenario 4: Example: Visualizing Thermal Comfort</u>

This use case (Figure 8) illustrates the interactions between end-users and external datasets with the system for the task of 'calculating and visualizing thermal comfort' within the building. The facility manager creates a digital twin by integrating and categorizing indoor thermostat data with the curated BIM model. POE analysts can walk around the BIM model and perform analysis to identify any potential gaps. Furthermore, the occupants can navigate the BIM model and have the option to provide feedback on their temperature comfort levels. The feedback is used as a data source to create the occupant satisfaction index that can be viewed by all the end-users (Facility managers, researchers, and occupants). Similar use cases can be developed for scenarios such as water use, energy use, and monitoring of IEQ.

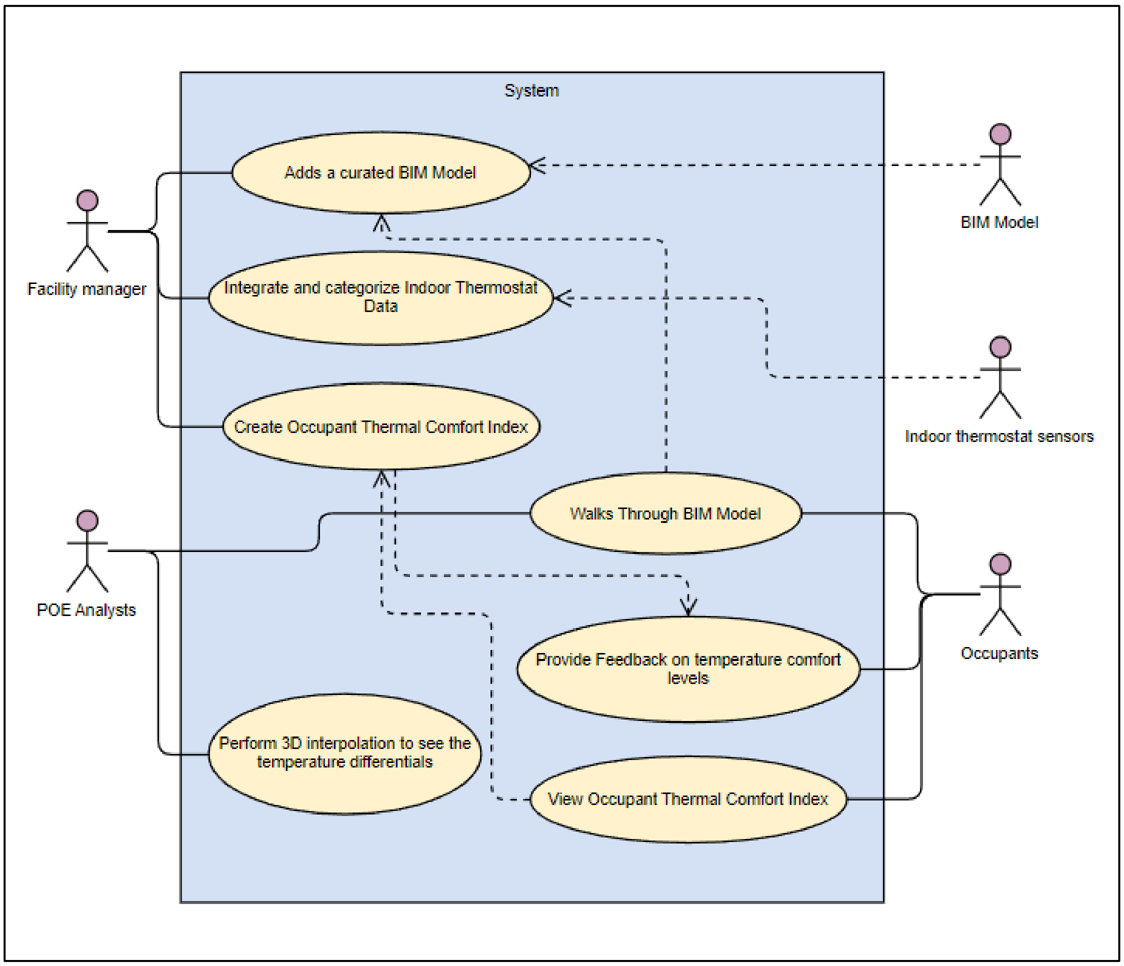


Figure 8: A use case example for visualizing and calculating thermal comfort within the building

3.5.2. List of system requirements

From the use case scenarios, the requirements of a system that can integrate BIM, GIS, and sensors' data are listed below:

- Integrate geo-referenced BIM Model
- Integrate building management sensors' data from database or spreadsheet
- Categorize and co-relate the sensors data within appropriate space
- Create 3D visualization based on KPI threshold values
- Visualize KPI with respect to time and space. i.e., able to see different values at user-defined time intervals
- Create charts for KPI calculations
- Customize Visualization to demonstrate desired threshold levels for different KPIs
- Incorporate Occupant's Feedback and provide a subjective occupant comfort index

3.6. Phase 2: BIM – IOT – GIS integration

This section describes the detailed procedure followed for the integration of a BIM model created in Revit and sensors' data from a spreadsheet to ArcGIS Pro. The series of experiments are conducted in alignment with use cases. The test results are used to recommend an optimized workflow (section 5.4) that can be replicated for other projects.

3.6.1. Digital Infrastructure

- Hardware
    - The laptop used for hosting STTC digital twin has the following configurations: Intel i5 8th generation processor, 16 GB RAM, 512 GB SSD, and 4GB Nvidia GTX 1050Ti GPU.

- Software

All the software mentioned below have academic licenses distributed through the University of Victoria.

- *Revit by Autodesk: Revit 2020*

  Revit is parametric modeling software for architecture, engineering, and construction purposes (Autodesk Revit Website). It is one of the most-used 3D modeling software in the industry. Moreover, it has numerous features for interoperability and integration with other software.

- *Excel 2016*

  Most of the sensors log their data into the database format. And that database can be exported into the comma-separated file format (.csv) that can be opened via Excel. For this study, excel is used as a source provider software for building sensors data.

- *ArcGIS Pro: 2.6 onwards*

  ArcGIS Pro is a GIS software that supports visualization, advanced analysis, and data management in 2D, 3D, and 4D. ArcGIS Pro has interoperability with Revit from version 2.6 onwards.

3.6.2. Tests

This section describes four tests conducted for demonstrating the development of a digital twin by integrating BIM model (Revit) and sensors' data (Excel) to ArcGIS Pro. These tests demonstrate the step-by-step procedure followed to achieve the goal for use case scenario #4: visualizing thermal comfort (Section 3.5.1, Scenario 4).

<u>Project scenario:</u>

A hypothetical project scenario has been considered for the tests. The building located on the campus of the University of Victoria is modeled using Revit. The largest area of the building is equipped with indoor thermostat sensors. The auxiliary sensor dataset is created in excel. The coordinate system *WGS 84 UTM Zone 10 N* is used for geo-referencing both ArcGIS Pro and Revit models (Appendix I).

3.6.2.1. Test 1: Adding the Revit model to ArcGIS Pro

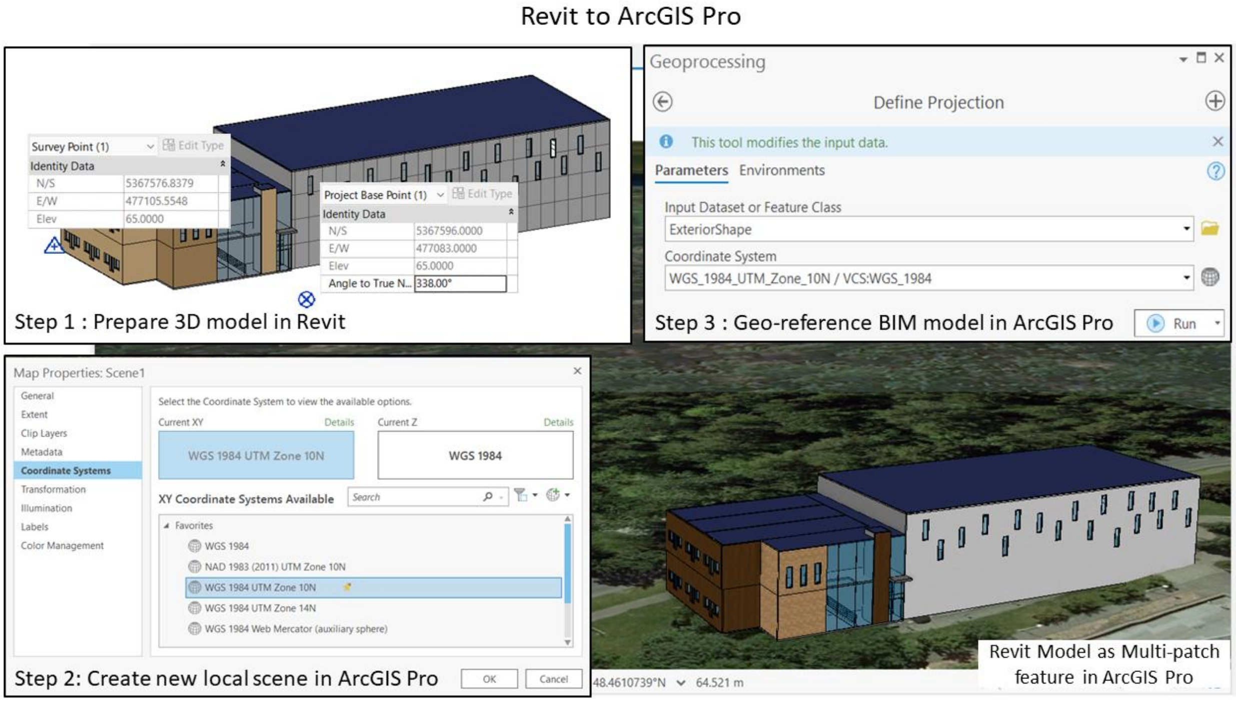


Figure 9: Procedure for importing Revit model to ArcGIS Pro

<u>Procedure:</u>

- Geo-reference Revit Model using *Project Base Point* and *Survey Point* as shown in step 1 Figure 9. ArcGIS Pro is not usually part of the BIM workflows in the AEC industry; therefore, the values of these reference points are taken from Google Earth Pro. However, ArcGIS can also provide the value of the coordinates.

- Create a new local scene in ArcGIS Pro and assign *WGS 84 UTM Zone 10 N* as the projected coordinate system for this project. Refer to Appendix 1 for types of coordination systems.

- Import the Revit Model into ArcGIS Pro and place it at the correct location by using the *Define Projection* tool.

Results & Discussions:

- From version 2.6, ArcGIS Pro automatically converts Revit Files to multi-patch features. As shown on the bottom right of Figure 9, the Revit model has been imported at the correct location in ArcGIS Pro.

3.6.2.2. Test 2: Adding sensors' locations to ArcGIS Pro

Modeling sensors' locations in a BIM model is not a part of a regular workflow for most BIM projects in the AEC industry. Moreover, POE involves a lot of spot measurement data. The purpose of this test is to determine how to import the sensors' locations in ArcGIS Pro in such a way that it can be used for various analyses and visualization for POE.

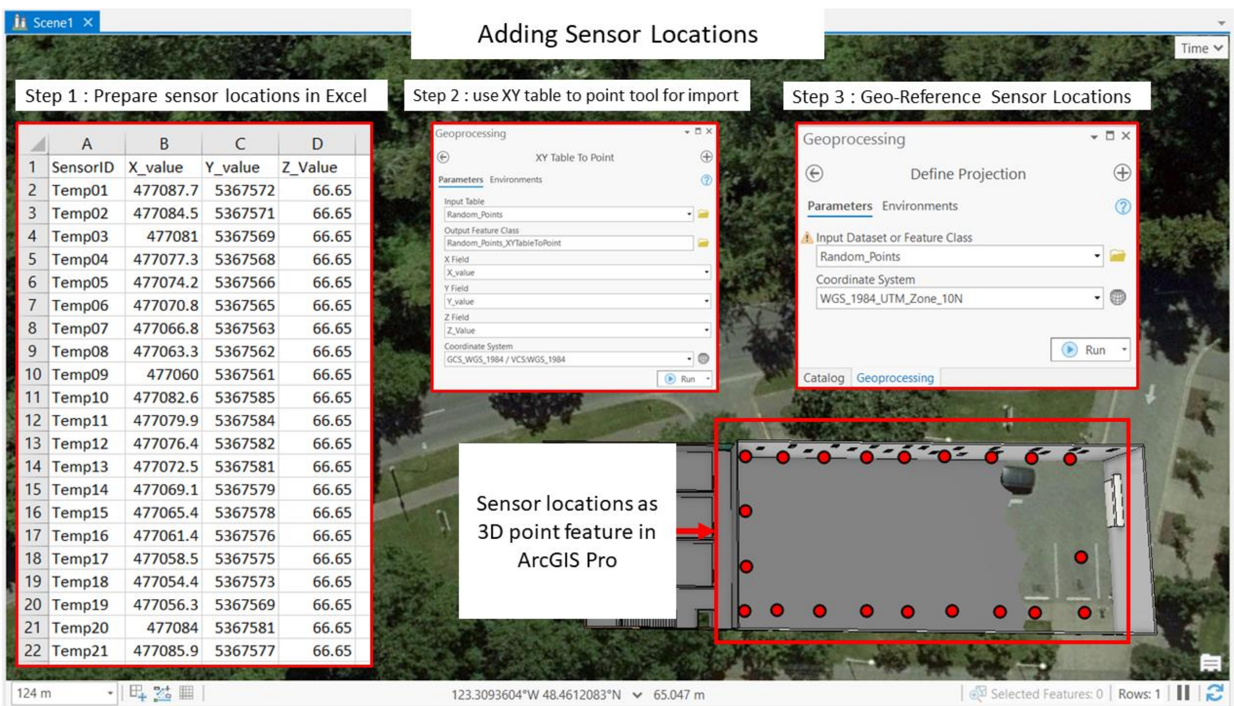


Figure 10: Adding sensor locations as 3D point features

Procedure:

- Determine coordinates of indoor thermostat sensors in ArcGIS Pro and prepare an excel file containing X, Y, and Z values of the locations as shown in Step 1, Figure 10. X value, Y value and Z value corresponds to latitude, longitude, and elevation, respectively.

- Import sensors' locations as a point feature class in ArcGIS Pro by using XY Table to Point geoprocessing tool
- Place the imported sensors to the correct location by using the Define Projection tool and assign the same project coordination system as the project.

Results & Discussions:

- As shown in Figure 10, the sensors' data imported as a point feature class are very useful in categorizing and distinguishing between various sensor types. Therefore, adding sensors as 3D points would be useful for attaching values to correct sensor locations and streamline the integration process in ArcGIS Pro. The sensors imported as 3D location points represent the value measured and logged by sensors. The same procedure can be followed for the spot measurements taken for different IEQ parameters for POE.

3.6.2.3. Test 3: Adding Sensors Data and enabling spatial-temporal visualization

IoT sensors log the measurement values at specified intervals of time. The spot measurements taken by the IEQ cart [3], [4] also log multiple values over a short period of time. Therefore, visualizing time-series datasets is essential for analysis in POE. This test describes the procedure followed for attaching time-dependent values to sensor locations and visualizing time-series datasets in 4D.

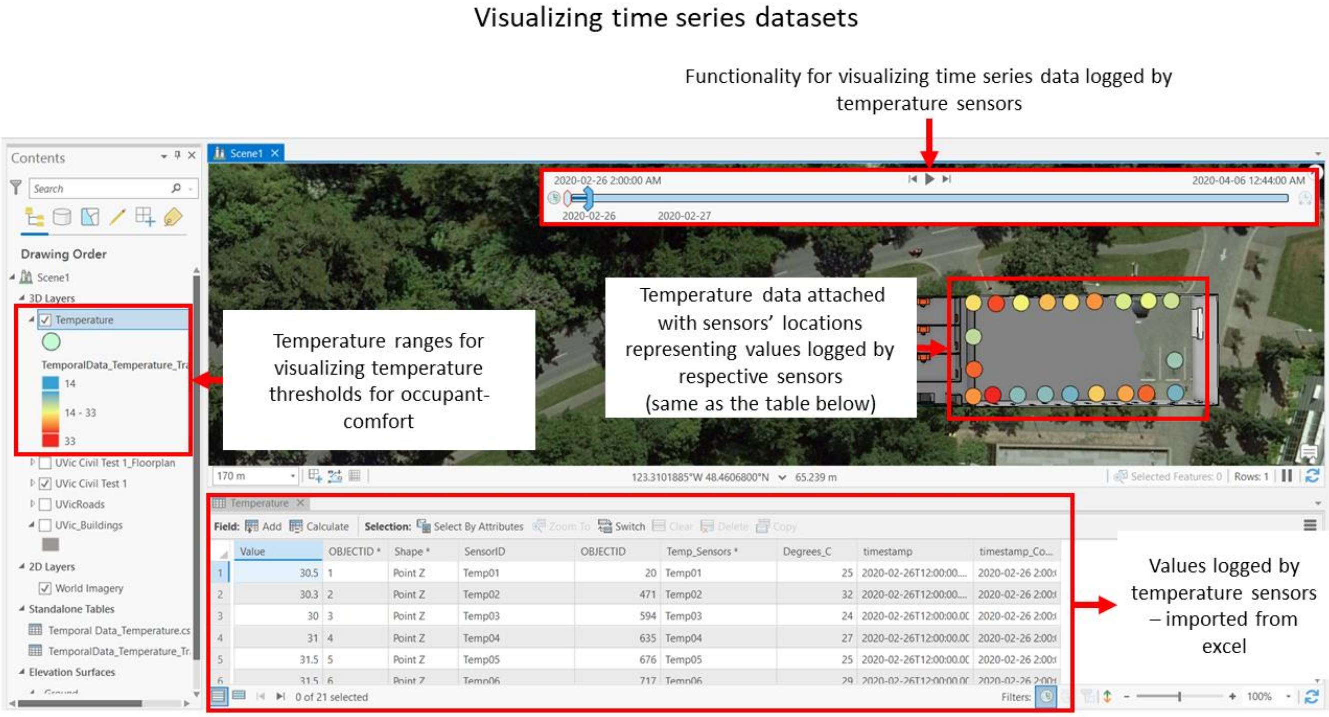


Figure 11: Adding and visualizing time-series data in ArcGIS Pro

Procedure:

- Prepare a database in Excel that contains measured temperature values with time. Please refer to Appendix II for further details.
- Import the excel file as a standalone table in the ArcGIS pro.
- Transpose the table in ArcGIS pro to get the temperature for each sensor at a given timestamp
- Perform a spatial joint to connect the Transposed table containing time-dependent temperature values with sensor locations (imported in step 2)
- Enable time in the feature layer and set the desired configuration to see the time-series data.

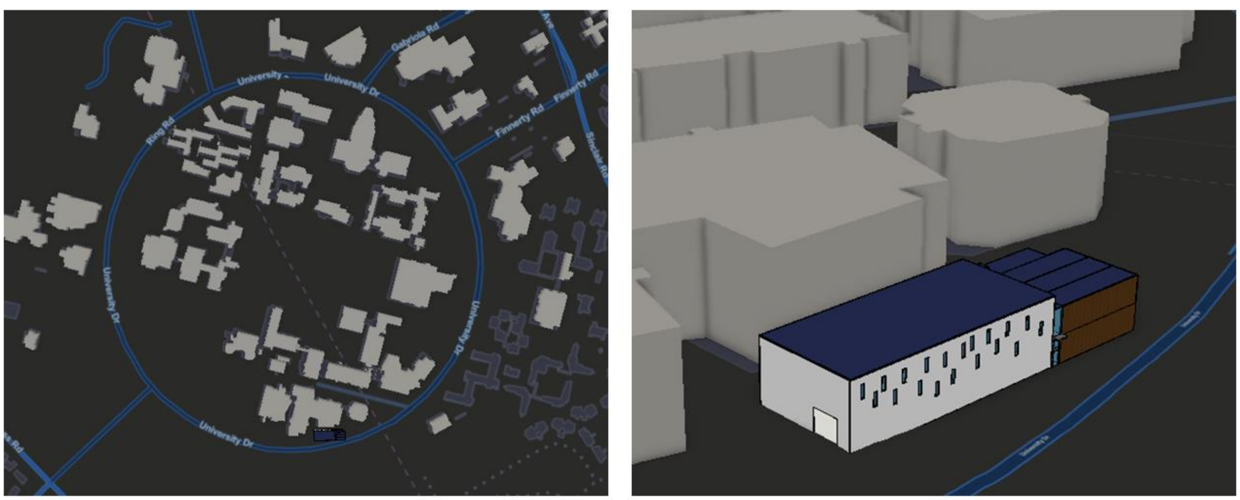
Results & Discussions:

- The measured indoor temperature data with time in the desired area within the BIM model can be seen in Figure 11. Visualizing time-series datasets of indoor temperature values in 3D has created a digital twin and enabled 4D visualization. The values can be categorized to determine the acceptable threshold values for indoor thermal comfort. The 4D visualization can be used to communicate the issues at a non-technical level.

3.6.2.4. Test 4: Adding Built Environment Data

BIM-based digital twin platforms have limited ways to incorporate information about the built environment. Adding more information also affects the performance of the model. BIM-GIS integration can overcome this limitation by adding the built environment data alongside the BIM model. This test aims to demonstrate that adding built environment data enhances the capacity of the digital twin for POE purposes.

Scalability



Top view of the University of Victoria Campus in ArcGIS Pro

Isometric view of the buildings around the BIM model in ArcGIS Pro

Figure 12: Adding surroundings in ArcGIS Pro

Procedure:

- Import the shapefiles for surrounding buildings.
- Note: The shapefiles are provided by the Geography Department from the University of Victoria
- Add the elevation to the shapefile for converting them from 2D to 3D

Results:

- As shown in Figure 12, the buildings surrounding the BIM model have been added to the BIM-GIS integrated digital twin. ArcGIS Pro can import numerous amounts of data types that can add more information to the digital twin. Moreover, more than one BIM model can be incorporated into the same ArcGIS Pro local scene. This feature addresses the scalability issues of existing digital twin platforms and can be used to compare the performance of multiple buildings within the same built environment.

3.7. Validation

This section discusses the validation techniques used to verify the accuracy and reliability of the information during and after the tests.

3.7.1. Geo-Reference check

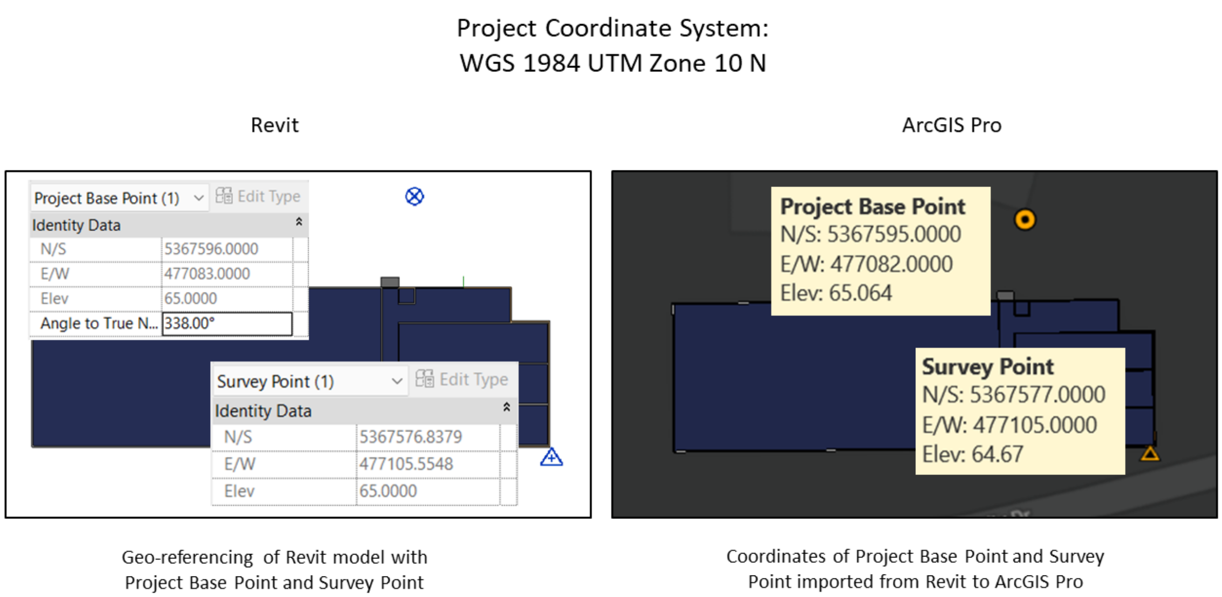


Figure 13: Comparison of the reference points

The Revit model is geo-referenced by using the project base point and survey point. These points are also carried over in ArcGIS Pro while importing the BIM model from Revit. Figure 13 compares the value of both Project Base Points and Survey Points. The differences in Project Base Point & Survey

Point are approximately 1m & 0.5m, respectively. The difference in elevation of the Survey Point is also approximately 0.6m.

Usually, the values of these reference points are provided by certified surveyors. Considering the values are taken from Google Earth Pro, the minor differences in the reference points are acceptable for this study.

3.7.2. Data transfer check

Revit maintains two types of parametric information about the component:

- Geometry and location
- Material properties

Not all the parametric information gets transferred to ArcGIS Pro from the Revit model. A data transfer check was performed for this study to ensure that ArcGIS Pro contains all the necessary information from the Revit model for the analysis & visualization related to POE.

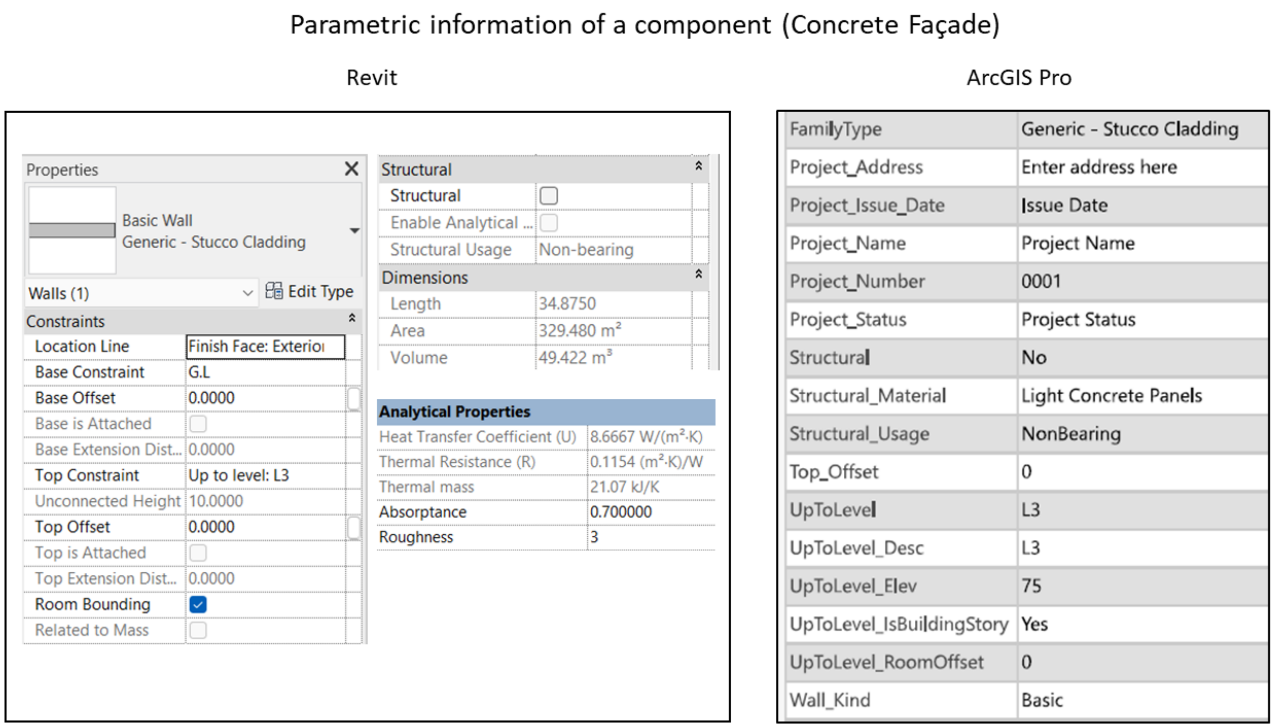


Figure 14: Comparison of parametric information of a concrete façade component

From Figure 14, it is evident that the analytical properties of the materials are not carried over during the Revit-ArcGIS Pro import. Moreover, ArcGIS Pro converts the Revit model into the multi-patch format that contains the geometry and location data of the component. Material properties do not get transferred over to ArcGIS Pro. However, ArcGIS Pro creates a spatial extent of Revit components that might be useful for the analytics. refer to Appendix III for more information on how ArcGIS Pro displays parametric information of Revit Components.

3.7.3. Visual checks

Revit's material library is data-rich and contains information about the texture and appearance of thousands of materials. Visual checks are used to verify if the visual representation of the data corresponds to their respective values. These checks are essential and frequently conducted for this project because 4D visualization of KPIs is essential for POE.

Visual checks confirmed that most of the data are transferred successfully. However, as compared in the Figure 15, ArcGIS Pro could not render the texture of the concrete panels imported from Revit model.

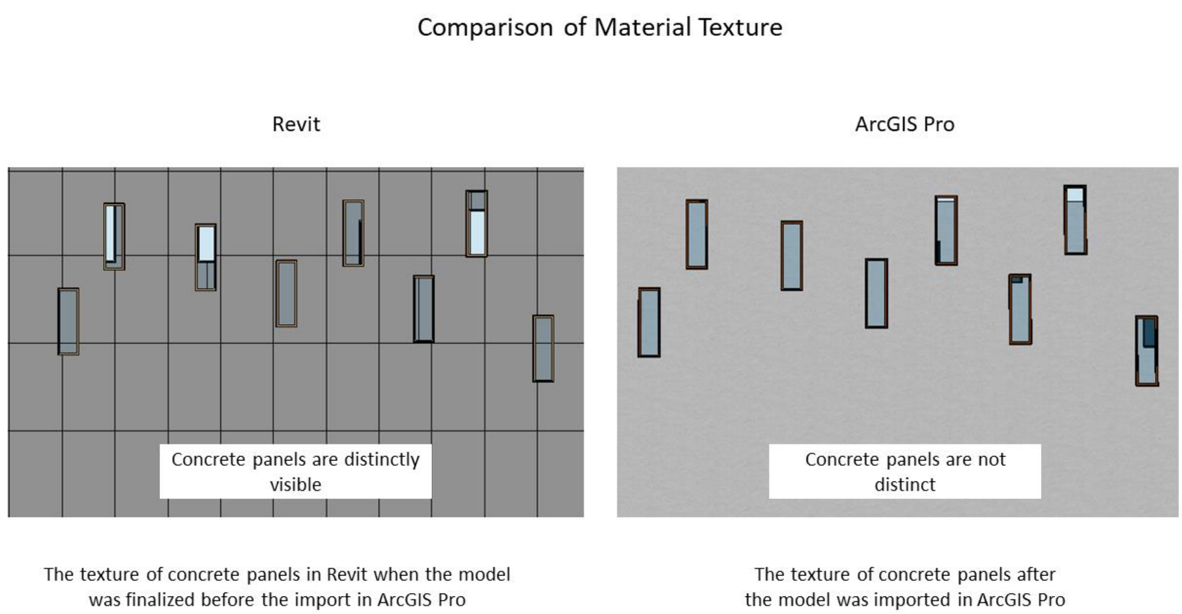


Figure 15: Comparison of the material texture of a concrete façade

3.8. Workflow recommendations

Based on the tests conducted in alignment with use case scenarios, an optimized workflow is recommended. The workflow can be used to create BIM-IoT-GIS-based digital twins for any building, facility, or infrastructure project.

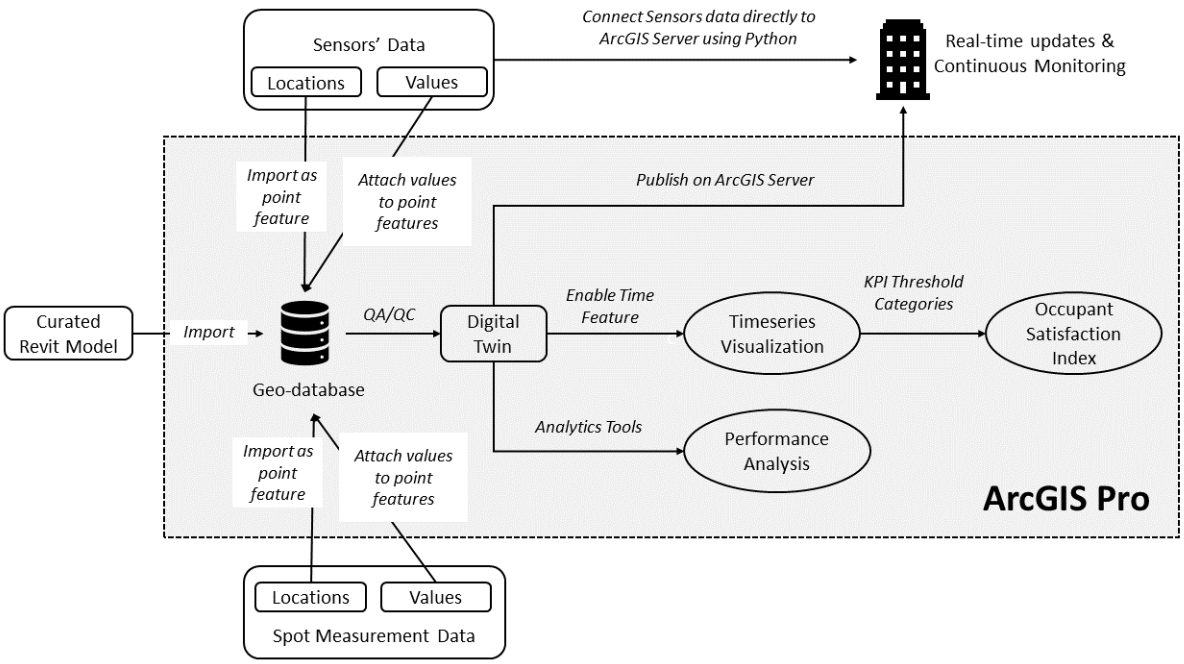


Figure 16: Streamlined workflow recommended for BIM-IOT-GIS integrations

Figure 16 illustrates the recommended workflow for integrating BIM models and sensors' data into ArcGIS Pro. Geo-database facilitates the editing and management of various data formats within the GIS environment [35]. Importing the Revit model and sensors' data to geo-database is the first step towards creating a digital twin for ArcGIS Pro. After the validation procedure, a digital twin can be established in the spatial-temporal 3D environment of ArcGIS Pro. Then, the spatial-temporal analytical tools can be used to analyze and visualize various key performance indicators in 4D. Overall, this workflow facilitates all three major applications of digital twin for POE: Continuous Monitoring, Data Analysis and Management, and Spatial-Temporal visualization of KPIs.

Although it was outside of the scope of this project, it would be possible to publish the ArcGIS model to an online server. Establishing a web-based digital twin could enable the sensors' data monitoring in real-time with the use of python script in ArcGIS Pro.

3.9. Limitations

This section describes the limitations experienced during the BIM-GIS integration.

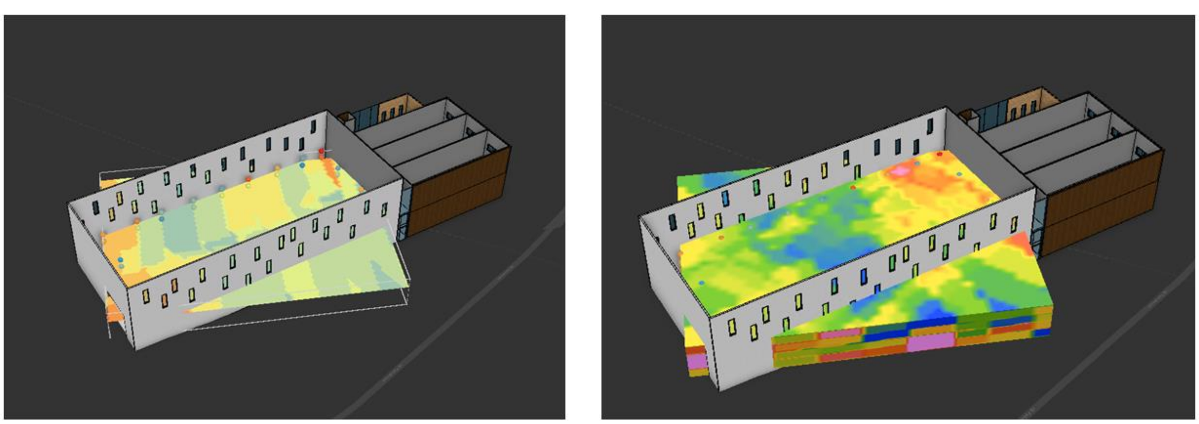
3.9.1. Hardware

Even though geo-database provides data management tools that enable the turning off of the data sets that are not required for specific tasks for POE, Revit and ArcGIS Pro both require high CPU & GPU power. When working with large datasets, appropriate breakdowns of the BIM model and the sensors' data suited to the POE requirements are recommended to mitigate the hardware limitations. Moreover, publishing the project on the ArcGIS server transfers some of the load from the hardware to the cloud computing server.

3.9.2. Software

ArcGIS Pro provides a suite of tools for spatial-temporal analysis. 3D interpolation tools are useful for calculating a distribution of a KPI, such as temperature over the desired area. Therefore, an attempt has been made to visualize the temperature distribution by using the hypothetical temperature values used in Test 3 (Appendix II). However, as shown in Figure 17, the 3D interpolation exceeded the extent of the area of the BIM model. Further investigation is required to determine the causes and potential solutions for this issue.

3D interpolation



Empirical Bayesian Kriging 3D (EBK3D) interpolation

3D Voxel layers constructed from EBK 3D interpolation

Figure 17: Errors encountered during EBK-3D interpolation

3.9.3. Other

The application of using BIM-GIS integration for hosting digital twins is relatively new. Also, there were only a few studies have considered using BIM-GIS as a preferred platform for sustainable facilities management. Therefore, the validation techniques used for this study were limited to the data transferred from Revit and Excel only. For BIM data, the open-sourced IFC file format is popular, as summarized in the literature review section; however, due to the direct import capabilities from ArcGIS Pro 2.6 onwards, Revit's native file format (.RVT) is used in this project.

3.10. Conclusions

Digital twin is an evolving concept in the AEC industry. It provides a centralized platform for data collection, modification, analysis, and visualization. Integration of BIM and GIS technologies enhances the capabilities of the digital twin by adding comprehensive geometric, semantic, parametric, and built environment data. Moreover, High-level applications and use case scenarios have clarified the requirements of a digital twin platform for POE. However, developing detailed use case scenarios will help create a customized system UI catered to POE. The tests explain the step-by-step procedure followed for BIM-IOT-GIS integration. There were no significant errors, discrepancies, or data loss during the integration. The results demonstrate that ArcGIS Pro is interoperable with Revit and sensors' database. Furthermore, it can handle large datasets and offers a wide range of tools and features for spatial-temporal data analysis and 4D visualization. Therefore, ArcGIS Pro can be used as a suitable digital twin platform that fulfills the system requirements for POE. Publishing the digital twin on the cloud-based server will help in mitigating some of the hardware and software limitations experienced during the tests. Also, the recommended workflow can be streamlined and reproduced for similar projects.

3.11. Next Steps

- The BIM-GIS integrated digital twin will be used in the high-level framework for the proof of concept for the next iteration of POE.
- A digital-twin integrated POE study will be conducted on the STTC building of Red River College located in Winnipeg, Manitoba.

Chapter 4: Digital-Twin-Enabled Post Occupancy Evaluations: A Proof of Concept

I.Tripathi, T. M. Froese, S. Mallory-Hill, "Digital-Twin-Enabled Post Occupancy Evaluations: A Proof of Concept", Unpublished Manuscript, 2022

4.1. Abstract

The design and construction of high-performance buildings have emerged as a preferred solution for reducing energy consumption and greenhouse gas emissions. However, not all buildings perform as they are designed. Post Occupancy Evaluations (POE) provide tools and methods to assess the performance of buildings compared to their design intent. This research aims to develop a proof of concept for digital-twin-enabled POE that leverages Building Information Modeling (BIM), Internet of Things (IoT) and Geographic Information Systems (GIS). First, a conceptual framework has been developed that illustrates the use of digital twins for POE procedure. Second, a case study has been conducted to determine the energy efficiency of the STTC building (Red River College, Manitoba) with respect to indoor thermal comfort using the digital-twin-enabled POE method. Third, an opinion-based survey and interview are conducted for the potential user feedback for the proposed digital-twin-enabled POE. The integration of BIM-IoT-GIS provides a dynamic platform to host a digital twin to facilitate POE. Moreover, visualizing thermal comfort relative to the weather and energy consumption will enable researchers and facilities management to suggest operational improvements. Based on the qualitative analysis of the potential user feedback, digital twins improve the overall efficiency of POE. However, further research is required to improve the accuracy of visualization.

4.2. Introduction

4.2.1. Background & Motivation

Sustainable buildings are designed to achieve environmental and economic performance over their lifetime by reducing energy consumption and greenhouse gas emissions. They leverage innovative and sustainable solutions that can create a nurturing environment and improve occupants' health, well-being and productivity [1]. Despite these sustainable initiatives, feedback about the buildings' actual performance relative to the design intent often gets overlooked [3]. Therefore, investigating the anticipated and the actual performance is essential for obtaining insights into the effectiveness of implemented design strategies, performance decay over time, and quality of the built environment relative to the occupant comfort [4], [6], [14].

POE provide tools and methods that can be used to obtain feedback for various parameters such as water, energy, indoor environmental quality and occupant comfort [3], [7]. Key Performance Indicators (KPIs) can be derived based on the obtained feedback to determine the performance gap. Methods for conducting POE vary according to the purpose and types of projects. Therefore, they are difficult to generalize [3]. Furthermore, manual data collection methods such as spot measurements for indoor environmental quality and occupant comfort feedback surveys are time-consuming [7]. Therefore, there is a need for a high-level conceptual framework for POE that can be customized for use across different types of projects and the nature of POE studies.

BIM provide detailed geometric and parametric information about the physical asset [11]. Moreover, IoT-based sensors offer cost-effective solutions for monitoring the changes in the built environment [15]. Furthermore, GIS can provide tools for spatial-temporal analysis and visualization [12]. Therefore, integrating BIM, IoT, and GIS technologies to create a digital twin can potentially address the limitations in the existing POE and provide a solid foundation to create a platform for POE, where data collection, analysis, and visualization can be facilitated by the BIM-IoT-GIS integrated digital twin [52].

This research aims to explore the following questions,

- How GIS-integrated digital twins can be leveraged for POE?
- Do such digital twins actually improve the overall POE procedure?

4.2.2. Objectives

The objectives of this research are as follows:

- To create a proof of concept for digital-twin-enabled POE
- To demonstrate the application of the proof of concept by conducting a pilot case study of a sustainable building, and

- To assess the effectiveness of digital-twin-enabled POE by obtaining opinion-based qualitative feedback from potential users.

Section 4.3 summarizes the related knowledge presented in the existing literature. Section 4.4 describes the detailed methodology followed to achieve the objectives. Section 4.5 provides a conceptual framework and discusses the procedure of conducting POE by using digital twins. Section 4.6 demonstrates the use case of the proof of concept by conducting a case study on the STTC building located at the Red River College campus. Section 4.7 validates the proof of concept by obtaining feedback from potential users across four main criteria to determine the effectiveness of the proof of concept.

4.3. Points of Departure

4.3.1. Observed Challenges in the Existing POE Method Recommended by the iiSBE Group

In 2014, the Candian chapter of the International Institute of Sustainable Built Environment (iiSBE) group conducted a Canada-wide POE study of nine buildings and discovered crucial performance gaps across a range of parameters such as energy, water and Indoor Environmental Quality (IEQ) [3]. Despite challenges, they successfully achieved their goal to create a standardized POE protocol for the Canadian industry. The 2014 iiSBE protocol provides a solid foundation for conducting POE. However, the dynamic nature of POE studies makes it difficult to generalize.

Table 2 describes the challenges observed in the 2014 iiSBE protocol that contains guidelines for data collection, management, analysis, and visualization for conducting POE.

Table 2: Observed Challenges in the existing POE [7]

Components	**Observed limitations**
1. Data Collection & Management	• Manual & Time consuming • Inaccurate occupancy • Lack of equipment benchmarking for spot measurements • Lack of provisions for integrating sensors
2. Data Analysis	• Manual KPI calculation • Processing of a large dataset • Challenging to incorporate occupant behavior
3. Visualization	• No provisions for visualization

A review paper by Li et al. [4] provides deeper insights into the current state of POE by analyzing 146 studies. They conclude five topics as a future direction of POE: (i) from one-off to continuing, (ii) from high-level to detailed, (iii) from researchers-oriented to owners/occupants oriented, (iv) from academia to industry, and (v) from independent to integrated.

4.3.2. Digital twins for Building Performance Evaluations

Digital twins can be defined as a virtual replica of a physical asset [36]. They leverage technologies such as BIM and IoT that enable continuous monitoring, multi-objective analysis and spatial-temporal visualization of the built environment [52]. Furthermore, digital twins create a common data environment for multi-disciplinary management of building operations and management data. Therefore, digital twins are expected to have a high impact on the management of sustainable facilities [53].

Project Dasher (figure 3) features a BIM-IoT-based digital twin developed by a multi-disciplinary research team at Autodesk [22]. They published a variety of research papers that covers various domains related to building performance assessments, such as recommendation for sensor networks [37] [38], occupancy tracking [39], mapping occupant behaviours [40], and performance monitoring [41]–[43]. Collectively, these papers contributed to the development of a BIM-IoT integrated digital twin that features an interactive user interface created with Autodesk Forge API. Moreover, it has a timeline feature for visualizing timeseries data and intuitive navigation features that ensures the smooth performance of the web-based model. Akro et al. [44] also proposed a BIM-IoT integrated methodology for visualizing indoor environment data using the Autodesk Forge API. However, both projects do not have provisions for including GIS environment data that helps to locate the digital twin with respect to the outside environment and also enables the monitoring of weather data in real-time [53]. While BIM technology excels at integrating and visualizing a wide range of building information, GIS excels at working with massive data sets, easy access to multiple layers of data, and geometric and temporal data manipulation and user interfaces.

Tripathi et al. [45] proposed to create a digital twin by combining three powerful technologies, BIM, IoT and GIS. Collectively, BIM and GIS provide an array of tools that can be utilized to create a conceptual framework for using digital twins for POE.

4.4. Methods

This section explains the methodology for developing a proof of concept digital-twin-enabled POE.

According to the Oxford English Dictionary, a proof of concept is '*evidence that shows a business proposal or a design idea works based on an experiment or a pilot project* [46].' Moreover, a proof of concept can be used to collect feedback from potential users.

In the context of this research, the proof of concept demonstrates a novel approach in conducting POE by providing a holistic framework for using BIM-IoT-GIS integrated digital twin during data collection, data analysis & data visualization. Findings are presented in three phases. Phase 1 demonstrates a holistic framework for the digital-twin-based POE. Phase 2 attempts to validate the proof of concept by piloting it on a real-life case study. Phase 3 contains the potential user feedback that is incorporated by obtaining opinion-based surveys. Table 3 provides an overview of the methods used during each research phase to achieve their respective objectives.

Table 3: An overview of methods and their expected outcomes for this research

Phases	**Methods**	**Expected Outcomes**
Phase 1 Proof of Concept	Digital twin enabled POE framework	The concept of conducting POE using a digital twin
Phase 2 Application	Case Study	A pilot demonstration of digital twin-based POE of STTC building, Red River College
Phase 3 Validation	Opinion-based Survey & Discussion	Effectiveness of the proof of concept

4.4.1. Phase 1: Conceptual framework for using digital twins to facilitate POE.

The conceptual framework for digital-twin-based POE is created by incorporating the digital twin with the traditional procedure of POE. For the context of this project, a digital twin is developed by integrating BIM model from Revit and sensors' data from excel with the GIS environment in ArcGIS Pro.

4.4.2. Phase 2: Case Study

To demonstrate the applicability of the proof of concept, a pilot digital twin is developed for the Skilled Trade and Technology Center (STTC) building located at the Red River College Campus in Winnipeg, Manitoba. The objectives of this case study are as follows:

- To determine the energy efficiency of the entire building,
- To use the STTC digital twin for visualizing occupant thermal comfort.

Figure 18: STTC building, Red River College

The STTC provides state-of-the-art facilities for skilled trades programs. It is designed to achieve a LEED Gold certification. It incorporates numerous sustainability features such as the central skylight, internal tubular skylights, high-performance façade, and photovoltaics. Moreover, it is equipped with over 1000 sensors and a weather station to measure performance, temperature, and moisture content.

The STTC digital twin is created based on the workflow illustrated in Figure 16. Hardware and software used to create the digital twin along with the STTC data sources are as follows:

- Hardware

The laptop used for hosting STTC digital twin has the following configurations: *Intel i5 8th generation processor, 16 GB RAM, 512 GB SSD, and 4GB Nvidia GTX 1050Ti GPU.*

- Software

All the software mentioned below have academic licenses distributed through the University of Victoria.

  - *Revit by Autodesk: Revit 2020*

  The project designer, Number Ten Architects, provided the STTC BIM model.

  - *Excel 2016*

  The STTC facilities management team provided raw weather data and indoor thermostat sensor data.

  - *ArcGIS Pro: 2.9*

  The STTC digital twin is created by integrating the BIM model provided by the architects and the sensors' data provided by the facilities management team at Red River College. The Revit – Excel – ArcGIS Pro integration is conducted based on the recommended workflow from Figure 16.

The energy efficiency of the STTC building is calculated by comparing the simulated energy consumption (from the LEED documentation) with the actual energy consumption (estimated by analyzing the electricity bills).

Due to the limitation in data availability and sub-metering, excluded energy related calculations are as follows:

- Electricity from solar panels is not considered in the calculations.
- Natural gas consumption is excluded from the calculations.

For visualizing the occupant thermal comfort, only classrooms located near the southern façade are considered for visualization and analysis. These classrooms usually represent consistent occupancy compared to other lab and workshop spaces.

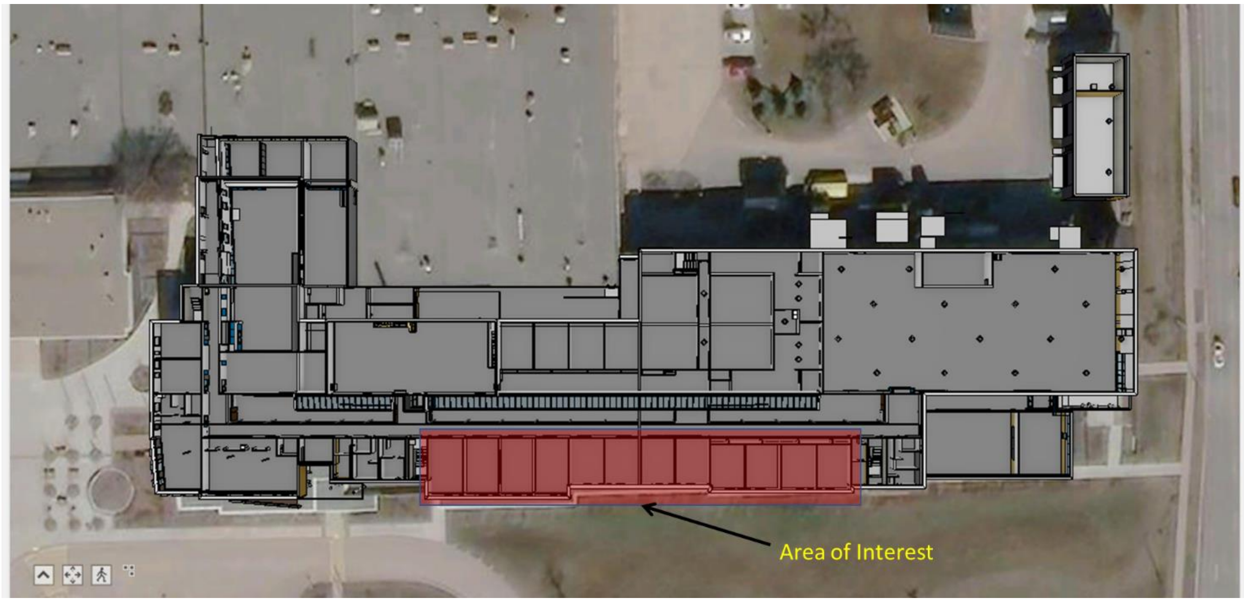


Figure 19: Second-floor classroom spaces located on the southern side

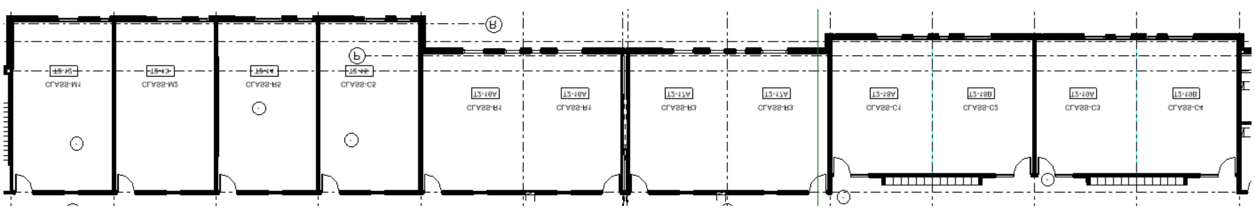


Figure 20: The 2D plan of the second-floor classroom spaces (the area of interest for this study)

The reference for the thermal comfort criteria is taken from ASHRAE 55 (2017) standards. Further details for indoor thermal comfort visualization are as follows:

- For simplification in visualization, for thermal comfort category ranges between 21°C – 26°C
- The relative humidity is excluded from the scope due to the lack of data availability.

4.4.3. Phase 3: Validation

To obtain user feedback on the proof of concept, an opinion-based survey and a focus group discussion were conducted. These studies received UVic's ethics approval (certificate number 21-0681). Based on the nature of the POE studies, the potential users are classified into two main groups.

Group 1 is comprised of the researchers (masters and doctoral students) working within various research labs in the Civil Engineering Department at UVic. The survey was distributed to researchers because of their nature of work; researchers constantly simplify their scientific findings to involve people across various technical and non-technical domains. Group 1 responses are quantified for a preliminary analysis.

Group 2 is comprised of the architecture, engineering, construction, and operations industry professionals who are familiar with the STTC building. A focus group interview was conducted with the designer to determine their preference in performance visualization for communication and decision-making.

A simple qualitative analysis was performed on the collected data (from both the group 1 survey and the group 2 interview) to determine the effectiveness of the proof of concept. Four criteria considered are as follows:

- Utility
- Accuracy
- Visualization preferences
- Efficiency

4.5. Phase 1: Proof of Concept

The proof of concept provides an overview of integrating digital twins in the traditional POE framework. This high-level proof of concept can be used to create custom methods across different types of projects and the nature of POE studies.

4.5.1. Conceptual Framework

This section explains the conceptual framework developed for digital-twin-enabled POE. Figure 21 illustrates how digital twins can be used for data collection, analysis & visualization during the POE process.

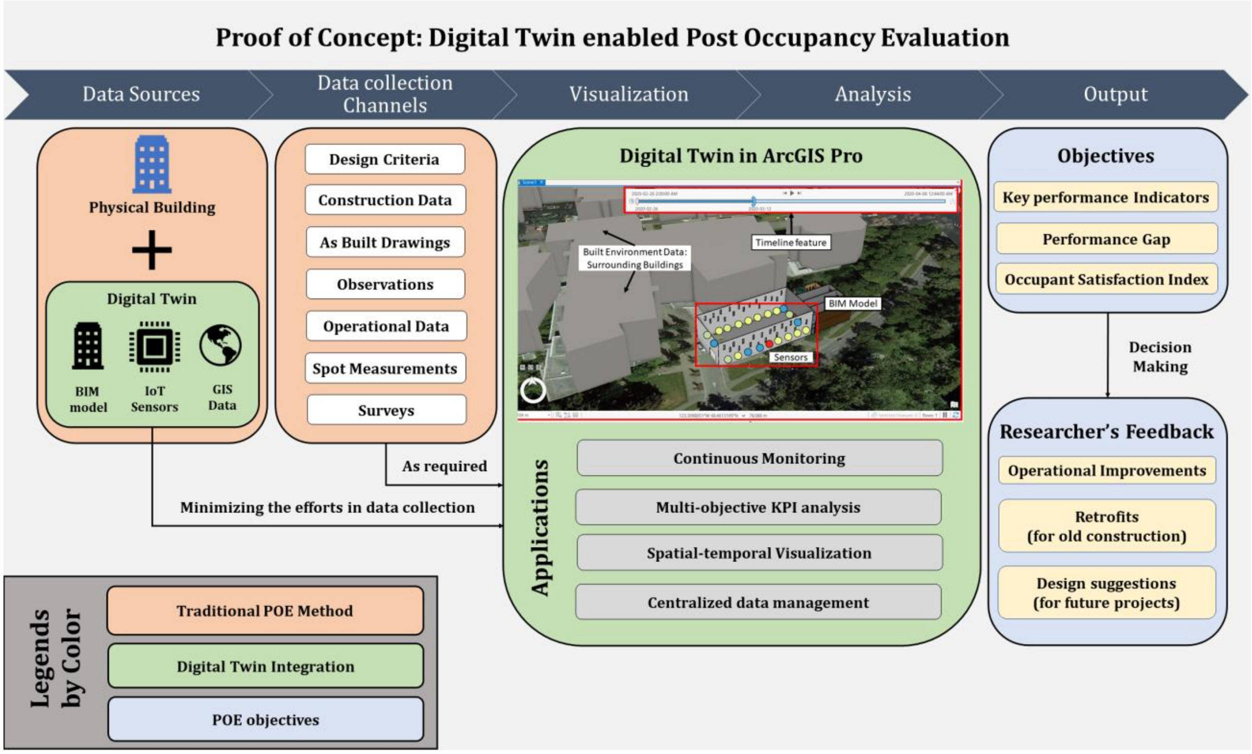


Figure 21: Conceptual framework demonstrating the digital-twin-enabled POE

This proposed framework suggests improvements using the digital twin (in green) to improve the existing POE methods (in orange). Improvements in the methodology are explained below.

- **Data collection**

Digital twins create an accurate virtual replica of a physical building. In the context of this study, BIM-IoT-GIS integration is proposed to create an effective digital twin for POE. Geometric data and material properties can be extracted from BIM models. Moreover, IoT-based sensors track the changes in the built environment and parameters related to various KPIs in real-time. GIS helps to locate the building with respect to its surroundings.

As per the POE requirements, desired data can be extracted anytime. Furthermore, data from manual measurements can be added to the digital twin if required. Thus, the proposed digital-twin-based method can be used as an effective and efficient comprehensive data repository platform.

- **Data Analysis & Visualization**

ArcGIS Pro offers a range of tools for spatial-temporal visualization and analysis. ArcGIS Pro categorizes the data in a structured geo-database format. These features promote ArcGIS Pro as a desirable data hub or a platform to host digital twins for POE.

In traditional POE, the collected data must be analyzed first to derive the results. The results are visualized and communicated in narrative descriptions, charts, and 2D drawings. However, in digital twin-based POE, data analysis and visualization can occur simultaneously. The spatial-temporal tracking of parameters has the potential to inform multi-objective analysis, where multiple KPIs can be visualized relative to one another. The multi-objective analysis opens new possibilities of investigations that are difficult to conduct when using traditional methods for POE. Therefore, digital twins improve the visualization of KPIs significantly compared to the traditional approaches such as excel-based visualizations.

- **Output/ Feedback**

POE plays a vital role in the feedback phase of the building life cycle. The key objective of POE is to calculate a set of KPIs to determine performance gaps in relation to occupant comfort. Communicating performance gaps is essential for analysts for suggesting operational improvements and providing design feedback. Digital twins can provide a centralized platform for professional collaborations.

4.5.2. Levels of Data Integration

BIM – IoT – GIS integration on the ArcGIS Pro server is recommended to develop a digital twin that updates in real-time. However, due to the potential privacy and security concerns, not all digital twins can be hosted on cloud-based servers where real-time data sync can be established. Table 4 describes different levels of data integration that can be applied across various types of projects.

Table 4: Levels of data integration for digital twin--based POE

Levels of integration	**Description**
Server-based integration	Ideally, BIM-IoT-GIS integrated digital twin is recommended to be hosted on ArcGIS Pro servers. The server-based model establishes a bi-directional data connection that facilitates KPI analysis & visualization for POE in real-time.
Software-based integration	Due to privacy and security concerns, most projects operate from the local secured servers of an academic or a professional organization. Moreover, if the building does not have sensors for measuring any KPI, then handheld equipment can be used to track the quality of the indoor environment. In this scenario, the digital twin can be categorized as partially integrated.
Project-specific integration	Project-specific digital twins can be created for independent POE studies to facilitate the POE procedure. Project-specific DT provides a solid starting point for existing buildings.

Continuous monitoring of the built environment and real-time KPI visualization within the digital twin are only possible for server-based data integration. For software-based and project-specific integration, appropriate updates to the data should be considered before developing the digital twin.

4.6. Phase 2: Case Study

This section discusses the digital-twin-based POE results conducted on the STTC Building.

4.6.1. The STTC Digital Twin

This project-specific digital twin (table 4) is created to pilot the proof of concept. Creating a server-based digital twin is out of scope for this study.

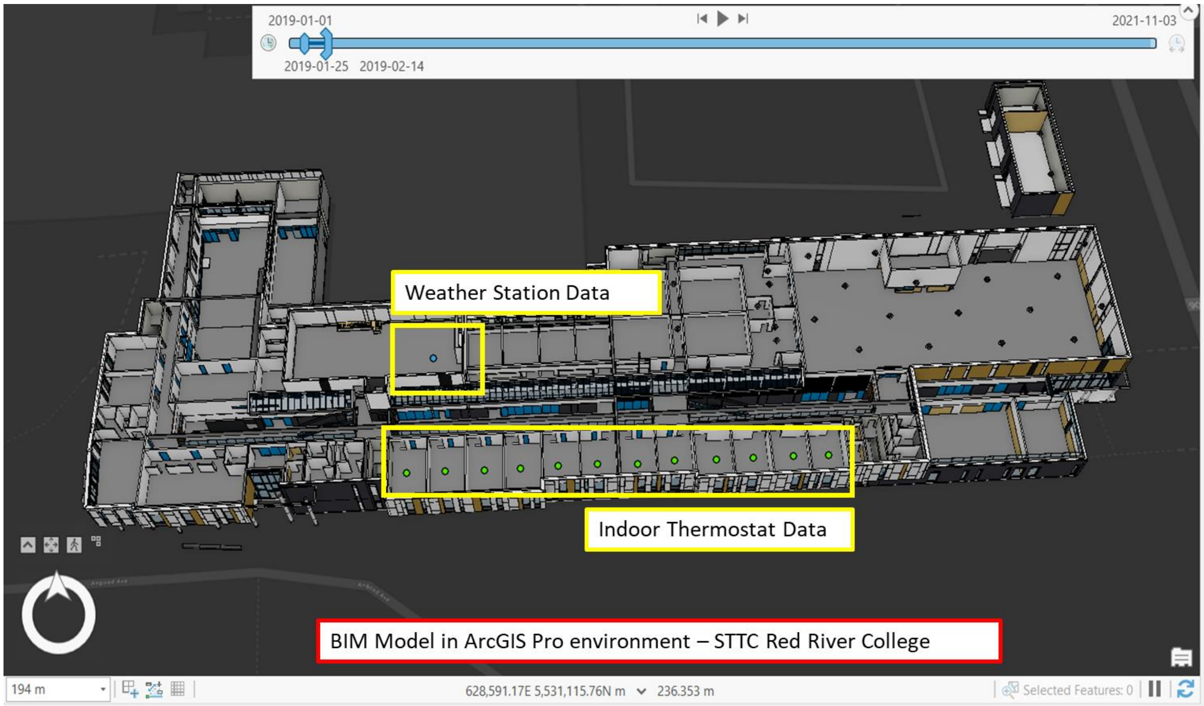


Figure 22: STTC digital twin in ArcGIS Pro

As illustrated in Figure 22, the STTC digital twin incorporates geometrical data from the BIM model provided by the designers and weather station data and indoor thermostat data provided by the STTC facilities management team.

4.6.2. Preliminary Energy Performance

Potential gaps in the energy performance are calculated by comparing simulated average yearly energy consumption vs the actual average yearly energy consumption.

- Simulated average yearly energy consumption

The value of simulated average yearly energy consumption is taken from the LEED document provided by the STTC facilities management team. The value is as follows:

<u>Simulated average yearly energy consumption ~ 1,540,000 KWH</u>

- Actual average yearly energy consumption

The yearly average of available data from 2019,2020 and 2021 is considered for these calculations.

Table 5: Actual Energy use in KWH

Year	Consumption (KWH)	Comments
2019	1,124,537	Usage for 9 months
2020	1,556,209	Usage for 12 months
2021	1,223,975	Usage for 11 months
Total usage	3,904,720	Total usage for 32 months (2019 -2021)
Avg monthly use	122,022	Calculation: = (Total usage / 32)
Avg yearly use	1,464,270	Calculation: = (Avg monthly use * 12) From 2019 - 2021

To improve the readability, the actual consumption value is rounded to the nearest thousand.

Actual average yearly energy consumption ~ 1,470,000 KWH

- Energy Performance

The difference between simulated and actual energy consumption,

= 1,540,000 KWH - 1,470,000 KWH

Average yearly energy Saved = 70,000 KWH

4.6.3. Visualizing the Occupant Thermal Comfort

As illustrated in Figure 23, the values from the indoor thermostat for the second-floor classroom area are color-coded in three ranges. The indoor thermostat values can be visualized with respect to time.

The computer used for hosting the STTC digital twin (a basic laptop) reached its capacity limit while attempting to add detailed resolution for the indoor thermostat values. Therefore, the thermal comfort range is classified into three different criteria only.

Figure 23: Visualizing occupant thermal comfort using STTC digital twin

4.7. Phase 3: Validation

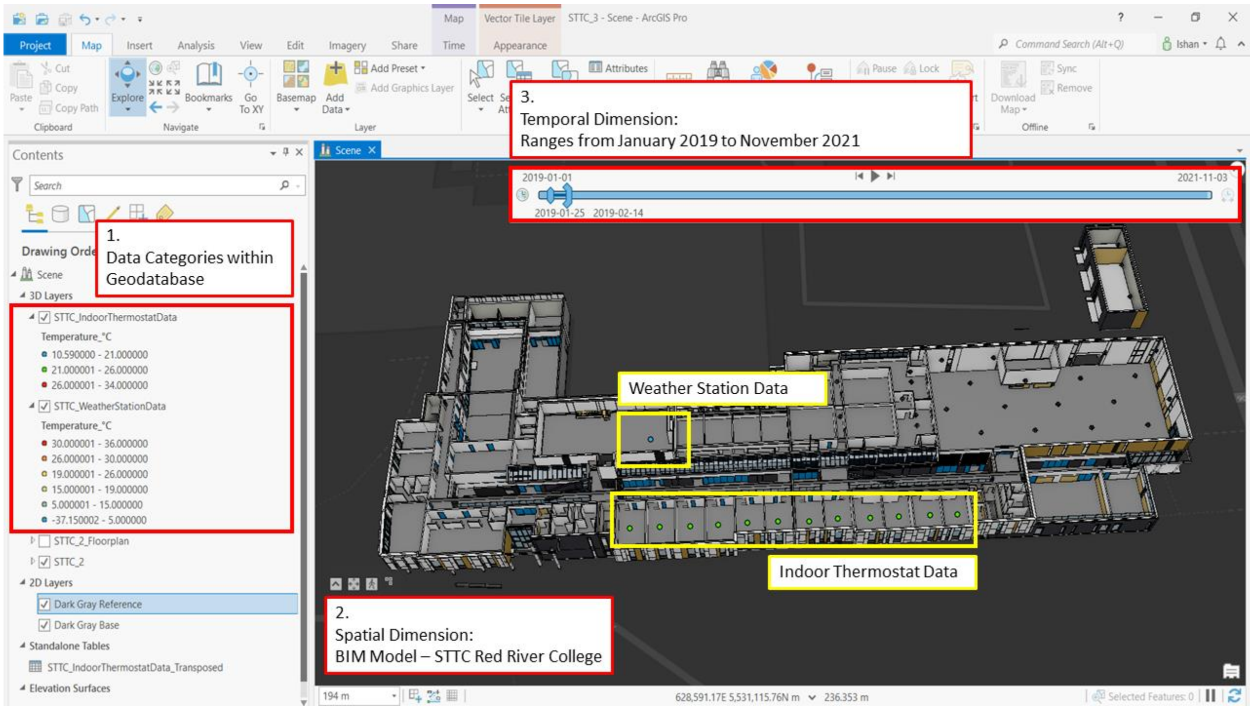


Figure 24: Image A: visualizing occupant thermal comfort using STTC digital twin

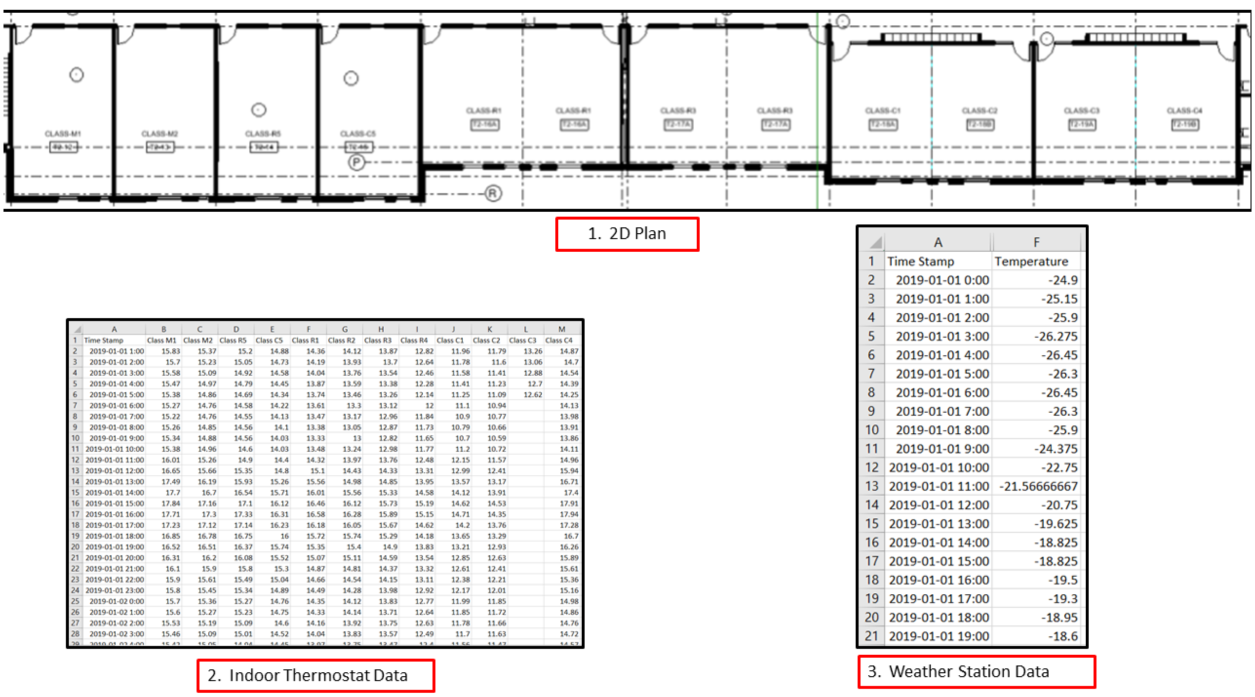


Figure 25: Image B: visualizing occupant comfort using the traditional method

Figure 24 and Figure 25 provide an overview of the digital-twin-based method and traditional excel-based method, respectively. These figures were presented to the participants who contributed to the opinion-based survey and focus group discussion. The survey questionnaire and the focus group discussion were designed to compare the traditional method of coordination between excel and 2D plans for analysis & visualization against the digital-twin-based POE method. The responses from the survey questionnaire (15 responses) and focus group discussion (3 participants) are summarized in four categories to validate the effectiveness of digital-twin-enabled POE.

4.7.1. Utility

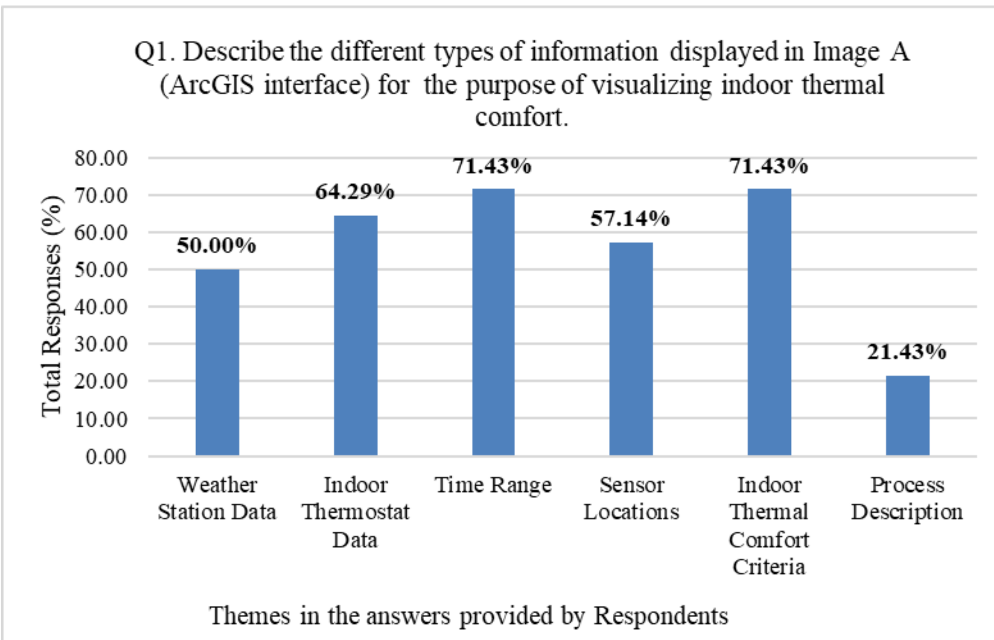


Figure 26: Types of information depicted by group 1 participants

Figure 26 summarizes the group 1 participant's responses to the open-ended question regarding identifying types of information displayed within the ArcGIS Pro interface. More than 50% of the participants identified five different types of information, which—when visualized together in the same interface—help to visualize the indoor thermal comfort. Around 22% of participants provided a detailed description of a procedure they might follow for visualizing indoor thermal comfort.

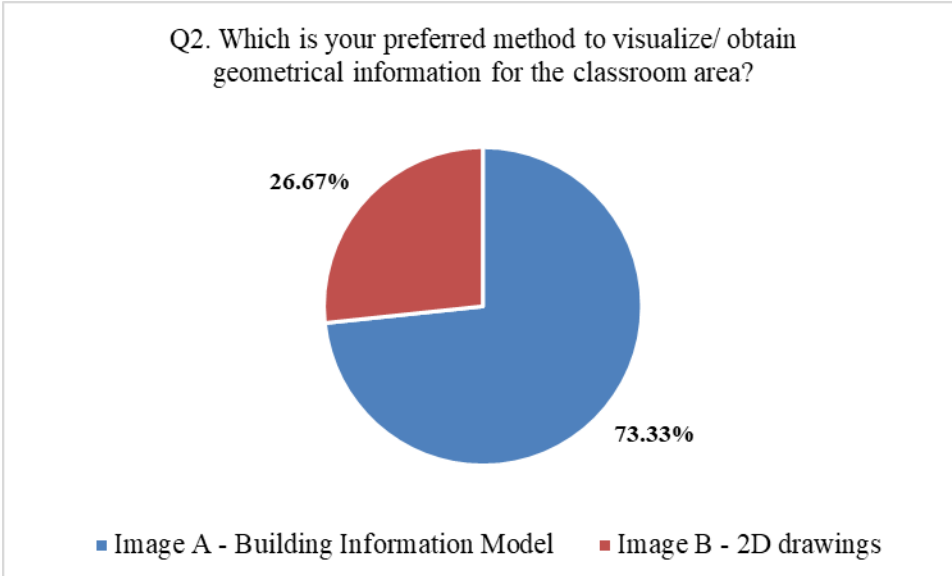


Figure 27: Group 1 responses to question 2 (Appendix VI)

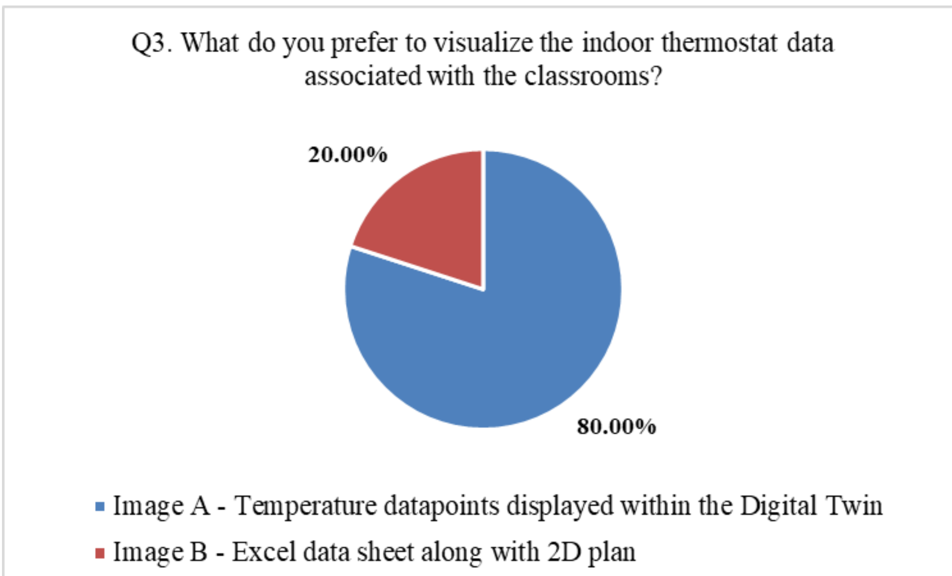


Figure 28: Group 1 responses to question 3 (Appendix VI)

When asked about their preferred method to obtain and visualize geometric data (Figure 27), almost 73% of participants preferred using digital twins, while 27% preferred using 2D plans. Similarly, for visualizing sensor values (Figure 28), for example, indoor thermostat values, 80% of the participants preferred using digital twins, compared to 20% who preferred using excel.

As a part of their design workflow, the designers are already using BIM-based performance visualization tools (for example, the Insight plugin for Revit), specifically for energy models. Because of climate change, the conventional weather prediction models are becoming inaccurate. The designers acknowledge the capabilities of BIM-IoT-GIS for tracking and visualizing weather data. Using the digital twin to track the weather adds value during the design feedback phase.

Based on this qualitative analysis, the utility of the digital-twin-enabled POE (Image A) can be considered higher than the traditional method (Image B).

4.7.2. Accuracy

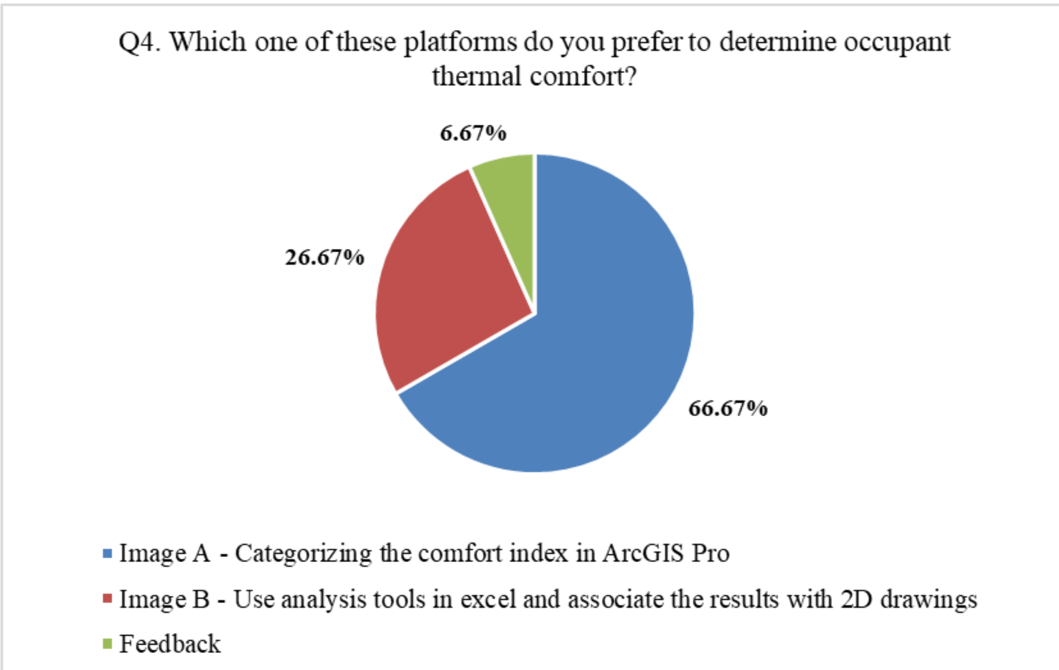


Figure 29: Group 1 responses to question 4 (Appendix VI)

When asked about their preference for determining occupant thermal comfort as a KPI (Figure 29), approximately 67% of participants preferred using the digital twin, while 27% preferred using excel.

Around 7% of participants provided feedback that, based on the given data and task, Excel presented a detailed data resolution, and the indoor thermostat values can be determined with an accuracy of two decimal points. In contrast, the digital twin presented a range of colour-coded data points that can be useful for visualizing thresholds but did not have a detailed resolution of indoor thermostat values. Designers shared the same point of view. For evaluating the accuracy, collectively, this detailed feedback outweighs the opinion of majority preference from group 1.

Based on this qualitative analysis, the accuracy of the digital-twin-enabled POE (Image A) can be considered lower than the traditional method (Image B).

4.7.3. Visualization Preferences

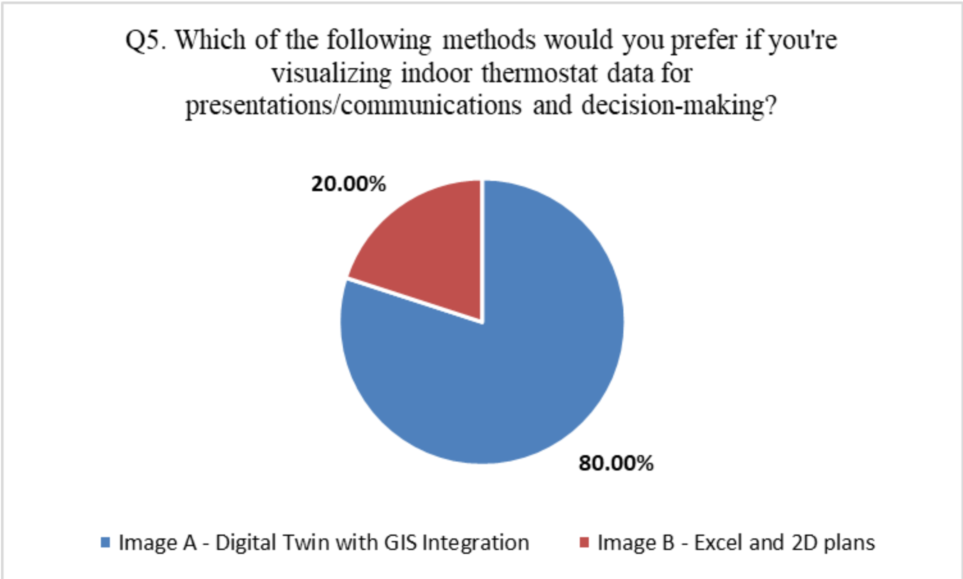


Figure 30: Group 1 responses to question 5 (Appendix VI)

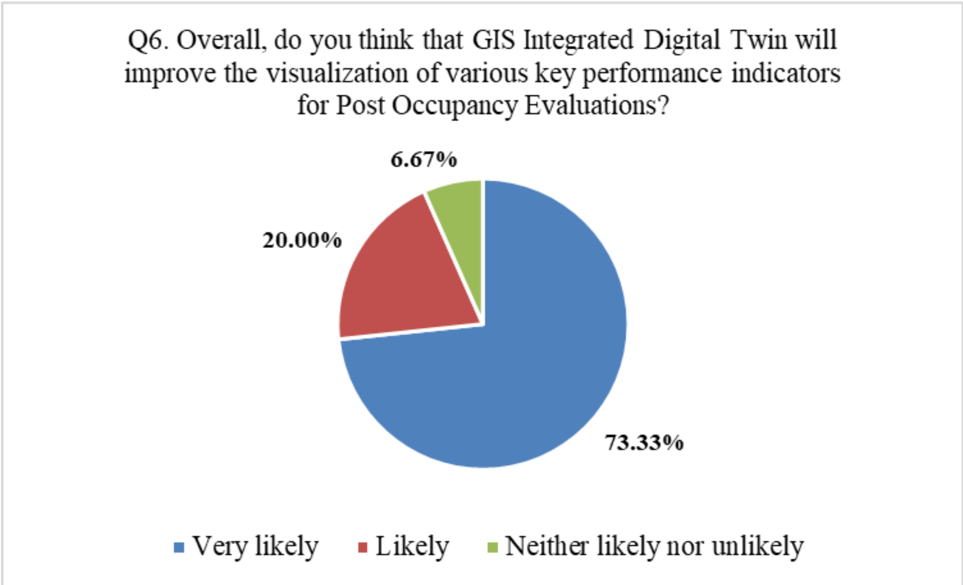


Figure 31: Group 1 responses to question 6 (Appendix VI)

As depicted in Figure 30, 80% of group 1 participants preferred using digital twins to communicate their findings for decision-making. Furthermore, from group 2, designers already use BIM models to communicate various design options with clients and stakeholders. Designers prefer to visualize the ‘carbon use intensity’ along with ‘energy use intensity’ and ‘thermal comfort’ for determining the success of their design. ‘Carbon use intensity’ should be included as a potential KPI for future POE studies.

When asked about their opinion (Figure 31), around 93% of the group 1 participants agreed that digital twins would improve KPI visualization for POE. Only around 7% of the participants had a neutral opinion. The designers from group 2 also perceive digital twins to be a way forward in the AECO industry.

Based on this qualitative analysis, the researchers and designers believe that digital twins will significantly improve the visualization of individual KPIs and performance gaps.

4.7.4. Efficiency

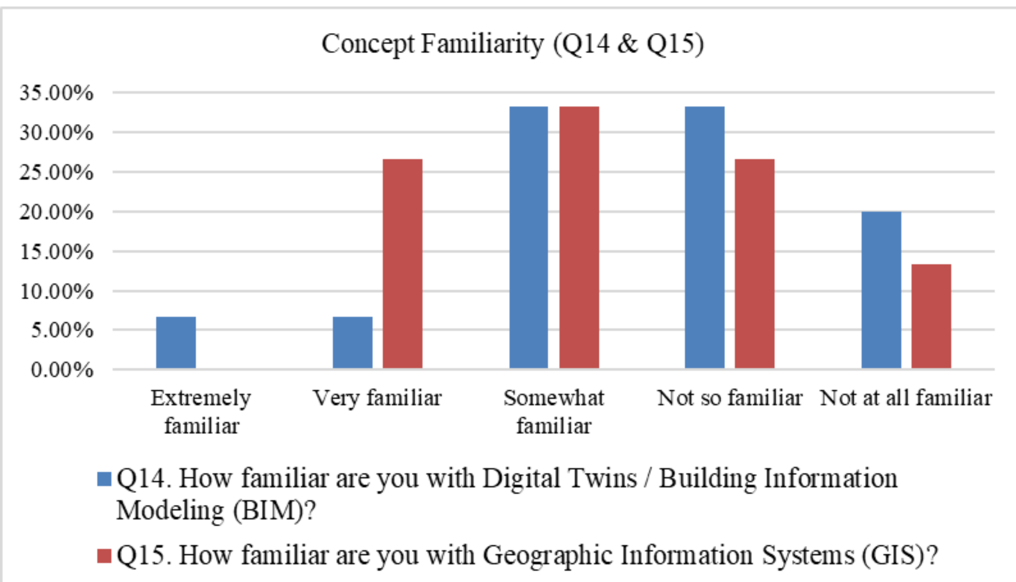


Figure 32: Group 1 responses to question 14 & 15 (Appendix VI)

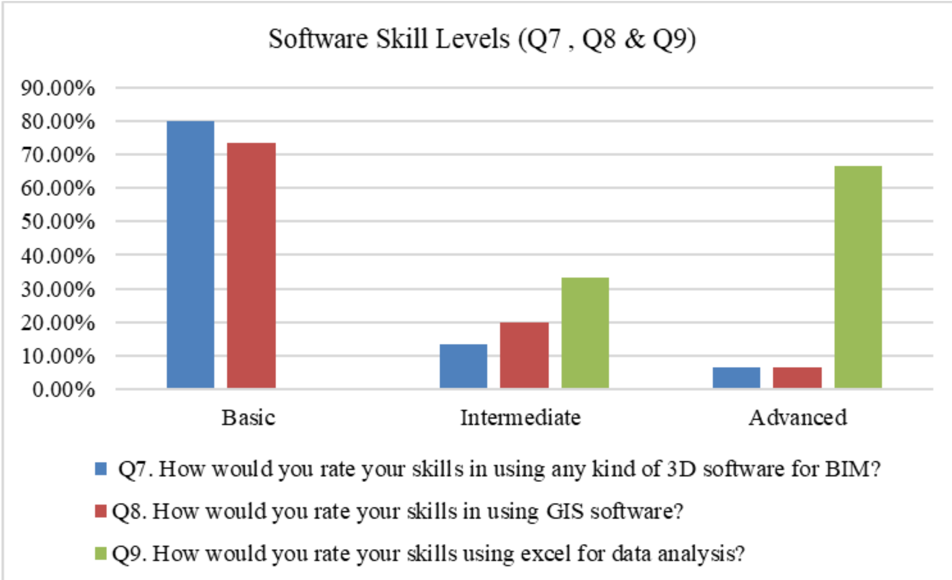


Figure 33: Group 1 responses to questions 7,8 & 9 (Appendix VI)

From the user perspective, researchers and analysts analyze the data and communicate their findings through effective visualization. On the other hand, the presented feedback helps designers acknowledge the effectiveness of design features and enables them to compare it with similar projects.

When asked about the familiarity of BIM and GIS concepts independently (Figure 32), approximately 50% of the group 1 participants responded to being familiar in both cases. Moreover, the designers from group 2 are using BIM as a part of their design workflow and had previous exposure to GIS.

Figure 33 presents a comparison of the skill level of group 1 participants. The majority of the researchers reported having basic skills in either BIM (around 80%) or GIS (around 70%). On the contrary, all the researchers have at least intermediate (around 30%) or advanced (around 70%) skills in using Excel for data analysis. In addition to that, the designers have intermediate skills in using BIM and basic skills in using GIS.

Therefore, the initial learning curve is anticipated to be higher when adapting BIM-IoT-GIS integrated digital twins for POE. This can result in lower efficiency at the beginning of the adaptation. However, once the familiarity with software and concepts increases, the efficiency is expected to increase over time.

4.8. Challenges & Recommendations

- Tracking occupancy is an ongoing challenge for POE due to privacy and security concerns. However, solutions such as the number of connections to local wifi networks are currently being evaluated for potential implementation. With spatial-temporal analysis and visualization tools, accurate occupancy can be mapped within the digital twin.

- The computer (hardware) used to host the digital twin reached its processing limits and crashed several times while trying to process large datasets in ArcGIS Pro. Publishing the digital twin on the ArcGIS Pro server will utilize Esri's cloud computing resources. Alternatively, creating a dedicated digital twin execution plan for POE can help designers break down one big BIM model into several small models that are easier to operate because of less processing load on the software.

- The BIM model has been curated and geo-referenced manually. Furthermore, the sensors' locations have been added manually to the digital twin. For optimum integration, the as-built model is recommended to be geo-referenced by a professional, and the sensors' locations should be included for indoor environment monitoring purposes.

- Due to the lack of data available for other parameters such as relative humidity, and lighting levels, only indoor thermostat data is considered for the case study. Further research is required to evaluate ArcGIS Pro's multi-objective analysis capabilities.

- Due to the COVID-19 pandemic, obtaining data for the case study was time-consuming. Therefore, only 1 KPI is calculated for the STTC building. Moreover, the ethics review application had a longer approval time.

- The quantitative analysis for validating the effectiveness of POE would have required multi-disciplinary coordination for observing the potential users and their ability to perform relevant tasks. Therefore, it is excluded from the scope of this research.

4.9. Conclusions

- The conceptual framework provides a solid base for customizing the digital-twin-based POE method across various types of projects and the purpose of POE studies. However, establishing semantics for POE and digital twins is essential for implementing digital-twin-based POE.

- The STTC building saves approximately 70,000 KWH/year based on the calculated energy performance. This positive energy performance can be linked to implemented sustainable features such as higher insulation for the envelope, skylights and tubes for natural lighting and solar panels. However, a detailed breakdown, such as sub-metering data, is required to identify the energy saved per category.

- BIM-IoT-GIS integrated digital twins offer a solid platform to streamline data collection, analysis and visualization for POE.

- GIS integration with the digital twin opens new possibilities for analysis and visualization by adding by tracking the change in the outdoor environment in real-time. Accurate outdoor weather data will improve the quality of future predictions.

- Visualizing thermal comfort with respect to the weather and energy consumption will enable researchers and facilities management to suggest operational improvements.

- Based on qualitative analysis, digital twins improve the overall procedure of POE. However, further investigation is necessary with upgraded hardware to add more resolution to the data, thus improving the overall accuracy.

4.10. Future work

- Propose a digital-twin-enabled POE methodology for UVic's upcoming ECS expansion project.

- Explore the evolution of the digital twin during each phase of the project lifecycle.

Chapter 5: Envisioning Digital-Twin-Enabled Post Occupancy Evaluations for UVic Engineering Expansion Project

I.Tripathi, T. M. Froese, S. Mallory-Hill, "Envisioning Digital Twin-Enabled Post Occupancy Evaluations for UVic Engineering Expansion Project", Unpublished Manuscript, CSCE 2022. (Under Review)

5.1. Abstract:

The University of Victoria (UVic) 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.

5.2. Introduction

The Civil Engineering department at the 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 [47]. 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 [48]. 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 [1]. 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 AECO industry for managing design, construction, and operations [19]. 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. Comparing this proposed methodology with a conventional methodology demonstrates the benefits of using digital twins for POE.

5.3. Points of Departure

5.3.1. Post Occupancy Evaluations (POE)

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 [4], [6], [14].

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 the values of Key Performance Indicators (KPIs) [3].

The methodology for conducting POE varies according to purpose and type of projects [4], [14]. 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 [7]. 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].

5.3.2. 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 AECO industry, a digital twin can be defined as a virtual replica of a physical asset [19]. Three key characteristics: representation of a physical building, bi-directional data exchange, and connection throughout the lifecycle of the building [49] 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 [19].

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 [50]. 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 Toronto Metropolitan University (formerly Ryerson), Toronto, Canada, supports pilot-scale research projects that focus on building controls, operations, and occupants' behavior towards building performance [51].

BIM models 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 [52]. 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.

5.4. 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 34 demonstrates the strategic approach considered for creating an overall framework that enables digital twins for POE.

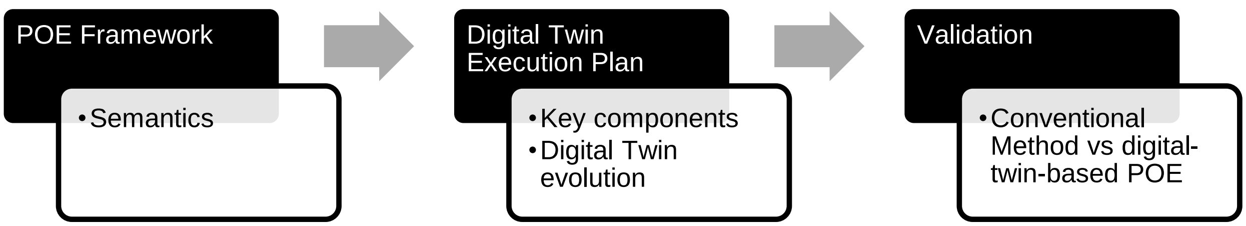


Figure 34: Strategic approach to creating a digital-twin-based POE methodology for UVic ECS expansion project

5.4.1. POE framework

The tools and techniques for conducting POE vary with the type of project and overall purpose [4]. 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).

5.4.2. 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.

5.4.3. Validation

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

5.5. Framework for the 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.

5.5.1. 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.

5.5.2. 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.

5.5.3. 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.

5.5.4. 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.

5.5.5. 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.

5.5.6. Key Performance Indicators (KPIs)

KPIs are useful to determine the effectiveness of parameters such as energy, water, IEQ, etc, that affect the sustainable performance of the building. Table 6 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 6: 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

5.6. Digital twin execution plan for POE

5.6.1. 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.

- For research: Simulations, predictive analysis, continuous monitoring, etc.
- For facilities management: 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

5.6.2. 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.

5.6.3. 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

5.6.4. 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

Table 7: 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

Sensors enable digital twin for continuous monitoring, effective visualization, and informed decision-making [19]. Table 7 gives an overview of the potential type of sensors that can be used within their respective systems according to their purpose.

iii. Data connections

Connecting IoT-based sensors with the BIM model establishes a bi-directional communication between physical building and its digital twin. Figure 35 below demonstrates integrating sensors' data with the BIM model using ArcGIS Pro (hypothetical building and data are used here for visual demonstration only).

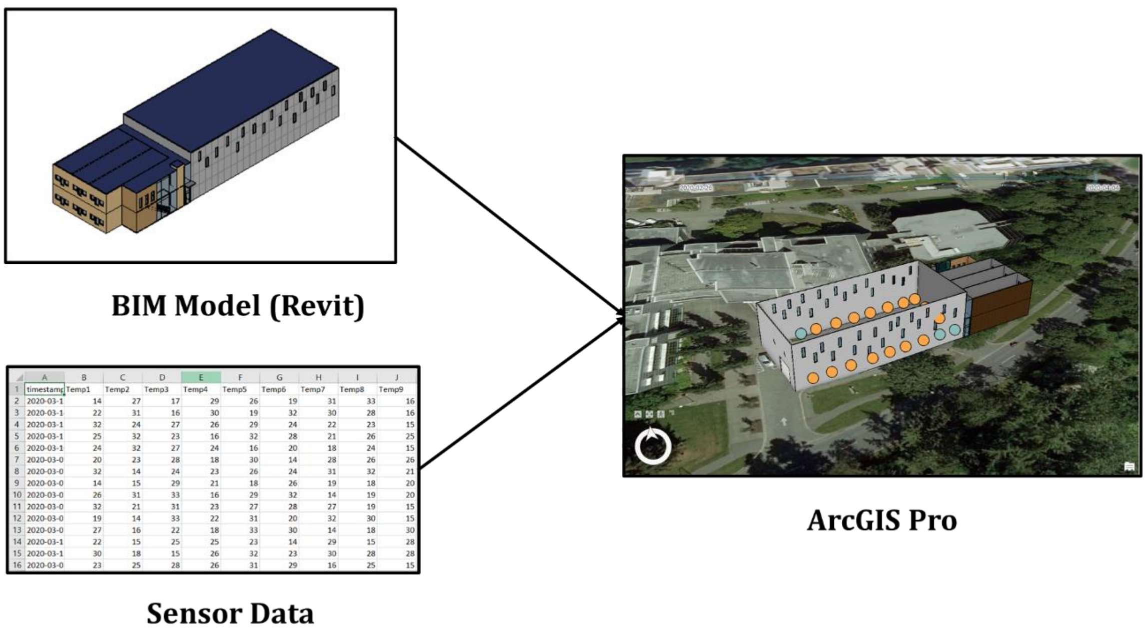


Figure 35: Example of connecting BIM model with sensors' data in ArcGIS Pro[15]

iv. Time (Refresh Rate)

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

- The refresh rate of sensors should be set as per the requirements of the corresponding research group
- Federated digital twin should be updated periodically; for example: once every term

5.6.5. Evolution of digital twins at each phase of the project

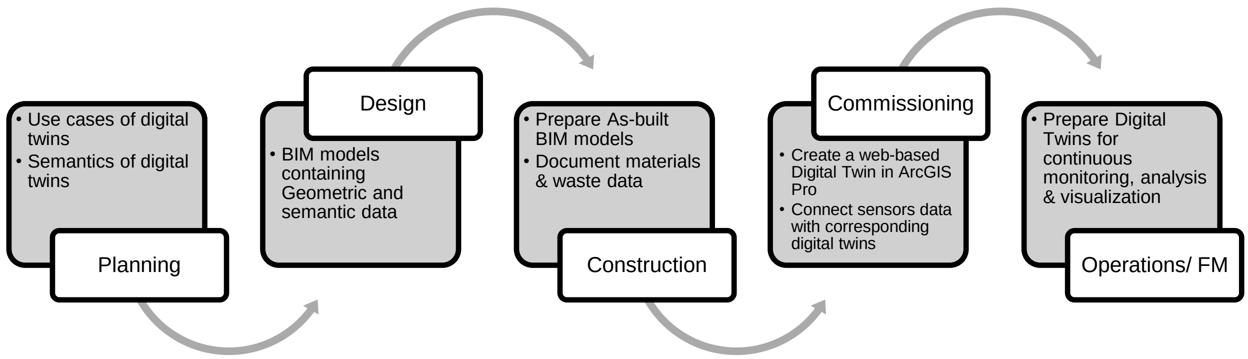


Figure 36: Evolution of digital twins

Figure 36 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 37, 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.

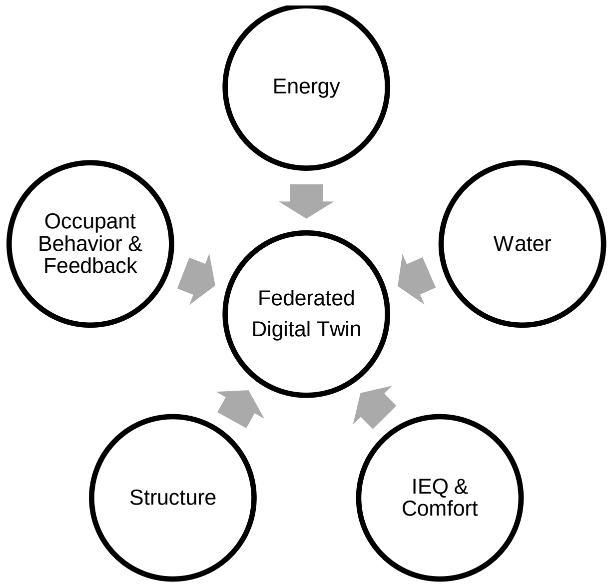


Figure 37: Conceptual illustration of a federated digital twin that is connected to various research-based digital twins

5.7. 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.

5.8. 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 8), 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* [53]. Evidently, this has resulted in time-consuming data collection methods and a lack of provisions for visualization for effective communication [7].

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 8, 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.

5.9. Conclusions

- POE 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.

Table 8: 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

Chapter 6: Summary, Contributions and Future Work

6.1. Summary

The ultimate goal of this research was to establish the method for the next generation of POE by using powerful technologies such as BIM, IoT and GIS to improve the overall efficiency.

Chapter 2: illustrated the current state of POE by analyzing the gaps in the 2014 POE protocol used by the iiSBE group. Using digital twins was recommended as a potential solution to address the gaps in data collection, analysis, and visualization.

Chapter 3: focused on creating a digital twin by integrating BIM, IoT and GIS that meets the requirements of POE. Four tests were conducted in alignment with the use case scenario to demonstrate how sensors' data can be integrated and visualized within digital twins. Based on lessons learned from the tests, a streamlined workflow has been recommended that can be customized and used across various types of POE projects.

Chapter 4: demonstrated how digital twins could be integrated with the existing POE methodology by providing a high-level proof of concept. Moreover, the proof of concept was validated by conducting a digital-twin-enabled POE on the STTC building. Finally, the potential user feedback survey and interview concluded that the majority of researchers and professionals preferred using digital twins for data acquisition and visualization.

Chapter 5: provided a high-level digital-twin-enabled POE methodology for the upcoming UVic's ECS expansion project. The semantics of digital-twin-based POE was discussed, followed by a digital twin execution plan that recommended the evolution of the digital twin at each phase of the project. The comparison of digital-twin-enabled POE with the traditional POE method demonstrated the benefits of using a digital twin for POE.

6.2. Contributions

The key contributions of this research are summarized as follows:

- The existing methodology observed gaps and proposed improvements are summarized in chapter 2. It analyzed the 2014 iiSBE protocol thoroughly; however, similar gaps can be observed across different types of POE projects.

- Chapter 3 presents a workflow to combine two powerful technologies with contrasting philosophies, BIM and GIS. BIM and sensors' data are essential to create a virtual replica of a building, also called a digital twin. Moreover, GIS adds spatial-temporal analytical and visualization capabilities to the digital twins. For example, the combination of BIM-IoT-GIS integrated digital twin can be used to track the live weather data relative to the building's performance. These multi-objective analytical capabilities will enable researchers and professionals to establish new correlations and obtain deeper insights that were not possible with the existing POE method.

- The proof of concept discussed in chapter 4 provides a holistic digital-twin-enabled POE framework that can be customized and used for various POE projects. Furthermore, the opinion-based user responses support the integration of POE with digital twins. Centralized digital twins can be used for asset management, building operations and post occupancy evaluations.

- The recommended digital-twin-enabled POE method for UVic's upcoming ECS expansion can be used to compare the performance of the existing facilities against the proposed sustainable facilities to prove the effectiveness of the incorporated sustainable features and their positive impacts on the environment.

6.3. Future Work

This research presents a holistic framework for using BIM models, GIS, and sensors' data to create a digital twin that can streamline the data collection, analysis, and visualization for POE. This integrated method can be the first step toward various types of research projects. Some examples are as follows,

- As recommended in Chapter 5, POE research for the upcoming UVic Engineering Expansion has excellent potential for a study such as 'Assessing the effectiveness of the proposed green buildings.'

- Create BIM-IoT-GIS integrated digital twins for managing large assets that consist of multiple buildings and natural assets.

- BIM-GIS integrated digital twins database for managing municipal level assets. For example, projects such as 'Energiesprong' can leverage the power of BIM – GIS integration to manage the database of affordable homes that can be retrofitted to be 'net-zero-energy' houses.

Appendix I – Projection system used for geo-referencing

WGS 1984 UTM Zone 10N

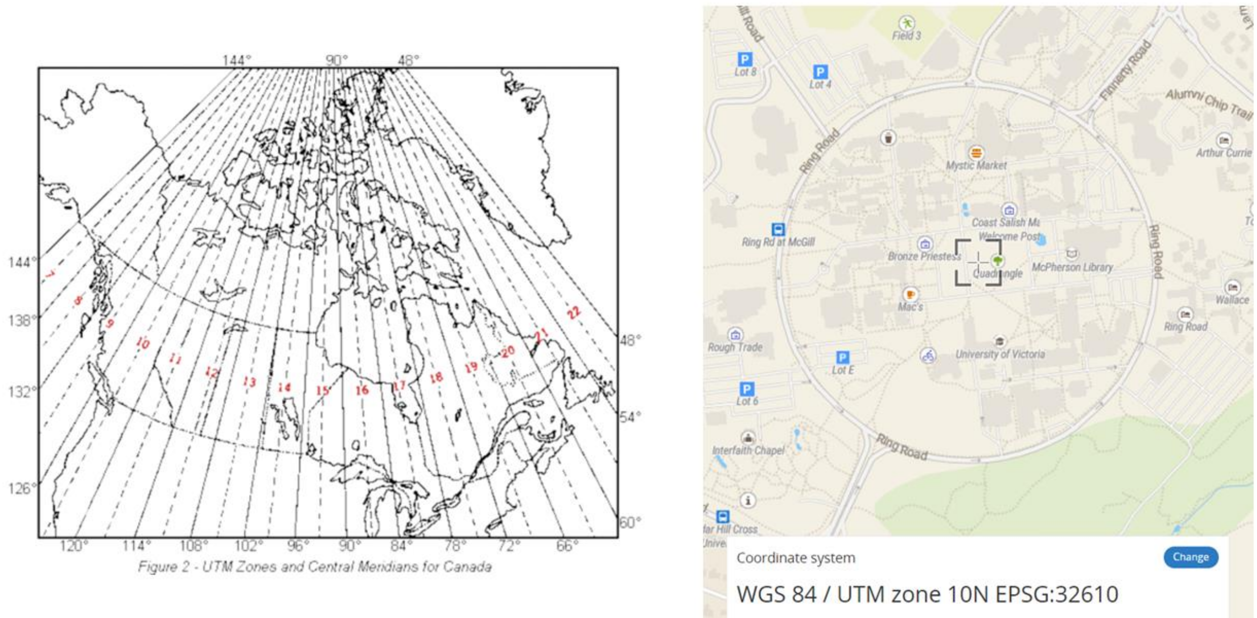


Figure 38: Projection system used for geo-referencing Revit model and ArcGIS Pro local scene
Image courtesy: Government Canada [54] & espg.io [55]

As shown in the Figure 38, the location of this project corresponds to the WGS 84: UTM Zone 10 N. This projection system is used to geo-reference both the Revit model and ArcGIS Pro local scene.

Appendix II – Sensor Dataset used for Test 3

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	timestamp	Temp1	Temp2	Temp3	Temp4	Temp5	Temp6	Temp7	Temp8	Temp9	Temp10	Temp11	Temp12	Temp13	Temp14	Temp15	Temp16	Temp17	Temp18	Temp19	Temp20	Temp21
2	2020-03-15T16:00:00.000Z	14	27	17	29	26	19	31	33	16	19	25	28	28	24	23	33	22	19	17	16	26
3	2020-03-14T16:00:00.000Z	22	31	16	30	19	32	30	28	16	15	26	25	22	22	28	28	18	15	16	31	14
4	2020-03-13T16:00:00.000Z	32	24	27	26	29	24	22	23	15	29	14	19	26	17	27	18	33	19	33	16	31
5	2020-03-11T16:00:00.000Z	25	32	23	16	32	28	21	26	25	15	30	14	25	22	18	31	26	22	28	28	14
6	2020-03-10T16:00:00.000Z	24	32	27	24	16	20	18	24	15	33	28	16	15	15	23	27	20	31	30	22	19
7	2020-03-09T16:00:00.000Z	20	23	28	18	30	14	28	26	26	27	26	23	19	14	15	32	14	33	31	27	25
8	2020-03-07T17:00:00.000Z	32	14	24	23	26	24	31	32	21	25	20	23	27	30	17	21	18	26	24	27	17
9	2020-03-06T17:00:00.000Z	14	15	29	21	18	26	19	18	20	14	20	19	22	26	32	19	21	31	31	15	31
10	2020-03-05T17:00:00.000Z	26	31	33	16	29	32	14	19	20	19	28	19	30	14	17	31	23	19	33	19	27
11	2020-03-03T17:00:00.000Z	32	21	31	23	27	28	27	19	15	19	28	25	33	16	17	16	25	27	17	24	17
12	2020-03-02T17:00:00.000Z	19	14	33	22	31	20	32	30	15	17	33	28	22	19	32	22	26	29	14	18	33
13	2020-03-01T17:00:00.000Z	27	16	22	18	33	30	14	18	30	30	28	33	14	30	22	25	20	31	27	18	22
14	2020-03-16T16:00:00.000Z	22	15	25	25	23	14	29	15	28	23	27	20	26	31	16	32	20	14	30	33	21
15	2020-03-12T17:00:00.000Z	30	18	15	26	32	23	30	28	28	29	28	28	26	15	24	30	22	24	24	25	24
16	2020-03-08T17:00:00.000Z	23	25	28	26	31	29	16	25	15	33	23	28	20	20	30	17	17	20	20	32	24
17	2020-03-17T12:00:00.000Z	20	30	29	22	27	24	23	21	26	17	31	14	31	29	20	18	31	31	32	31	20
18	2020-03-18T12:00:00.000Z	24	33	19	22	19	30	21	17	27	24	14	30	16	28	31	32	19	15	21	15	20
19	2020-03-19T12:00:00.000Z	31	18	14	17	19	17	20	20	15	20	29	32	20	16	15	28	24	22	14	14	16
20	2020-03-20T12:00:00.000Z	26	27	26	29	20	33	19	32	27	28	25	27	15	18	27	27	33	30	30	33	32
21	2020-02-26T12:00:00.000Z	25	32	24	27	25	29	22	23	21	29	33	17	17	16	26	28	31	16	18	31	20
22	2020-02-27T12:00:00.000Z	16	16	19	28	31	25	15	16	26	20	32	23	27	23	25	25	22	16	22	20	24
23	2020-02-28T12:00:00.000Z	31	32	25	24	28	25	25	24	20	14	15	16	23	22	19	16	19	28	14	32	20
24	2020-02-29T12:00:00.000Z	17	16	26	14	31	20	32	22	22	19	31	32	20	23	21	32	22	29	32	30	31
25	2020-03-04T12:00:00.000Z	16	29	16	16	28	30	26	28	28	20	29	14	20	19	28	17	27	24	21	25	33
26	2020-03-21T12:00:00.000Z	32	17	20	17	20	32	16	24	19	22	21	28	16	26	31	14	27	27	14	25	27
27	2020-03-22T12:00:00.000Z	23	20	25	26	19	22	15	17	28	25	30	26	15	24	22	15	17	25	21	19	25
28	2020-03-23T12:00:00.000Z	15	27	31	29	26	26	30	24	30	25	28	28	33	25	32	23	24	18	22	18	29
29	2020-03-24T12:00:00.000Z	30	32	28	31	22	33	25	25	14	30	19	32	31	17	22	33	29	24	20	27	23
30	2020-03-25T12:00:00.000Z	23	14	28	16	32	32	33	32	18	16	14	18	31	26	17	23	32	33	24	26	22
31	2020-03-26T12:00:00.000Z	19	14	22	25	28	32	30	33	28	21	26	17	32	15	30	31	21	23	26	28	32
32	2020-03-27T12:00:00.000Z	23	20	21	21	28	17	18	32	21	20	26	18	14	16	28	20	14	33	18	16	15
33	2020-03-28T12:00:00.000Z	25	32	14	20	27	27	16	25	16	29	33	23	31	20	15	28	14	19	19	24	19
34	2020-03-29T12:00:00.000Z	25	30	16	22	14	31	14	14	14	17	27	17	27	14	27	27	31	14	28	29	14
35	2020-03-30T12:00:00.000Z	32	25	19	20	22	33	28	26	32	22	25	14	27	29	23	21	26	28	22	28	21
36	2020-03-31T12:00:00.000Z	23	14	17	31	27	29	23	17	27	15	23	17	29	30	24	25	26	14	30	21	24
37	2020-04-01T12:00:00.000Z	22	18	23	29	33	28	18	16	28	31	25	28	17	16	30	23	24	26	28	15	20
38	2020-04-02T12:00:00.000Z	29	26	21	24	27	24	23	15	20	27	30	19	32	26	29	24	29	24	25	21	28
39	2020-04-03T20:26:00.000Z	17	29	30	22	30	22	24	25	29	17	29	19	18	15	24	28	16	28	20	25	14
40	2020-04-04T19:38:00.000Z	18	26	25	17	33	31	28	14	32	28	27	30	14	18	22	32	14	33	17	17	16
41	2020-04-05T19:54:00.000Z	31	23	25	18	32	25	15	14	16	14	31	17	32	25	33	18	23	21	26	31	29
42	2020-04-06T20:44:00.000Z	26	33	32	33	26	20	17	22	18	23	20	27	25	15	23	30	23	27	27	15	30

Figure 39: Timeseries data containing temperature values used for Test 3 (Figure 11)

Appendix III – Information Transferred from Revit to ArcGIS Pro

ElementType	SWall
Family	Basic Wall
Function	Exterior
Mark	<Null>
ObjectId	298166
OmniClass	<Null>
OmniClassDescription	<Null>
Typ_Mark	<Null>
Type	<Null>
DocName	UVic Civil Test 1
DocPath	C:\MASc Research - Ishan\01 BIM_ArcGIS Visualization\Test 1 - Revit to ArcGIS\UVic Civil Test 1.rvt
DocType	RVT
DocUpdate	2020-10-26 5:31:37 PM
Bldg_Name	
DocId	1.756983e+19
DocVer	2020
Base_Offset	0
BldgLevel_Desc	G.L
BldgLevel_Elev	65
BldgLevel_IsBuildingStory	Yes
BldgLevel_RoomOffset	0
Client_Name	Owner
ExtId	dbd21eb9-87fe-48ce-9232-98412f075a23-00048cb6
FamilyType	Generic – Stucco Cladding
Project_Address	Enter address here
Project_Issue_Date	Issue Date
Project_Name	Project Name
Project_Number	0001
Project_Status	Project Status
Structural	No

Figure 40: Parametric data of concrete façade in ArcGIS Pro (Data transfer checks, section 3.7.2)

Appendix IV: Preparing STTC's Revit model for ArcGIS Pro Integration

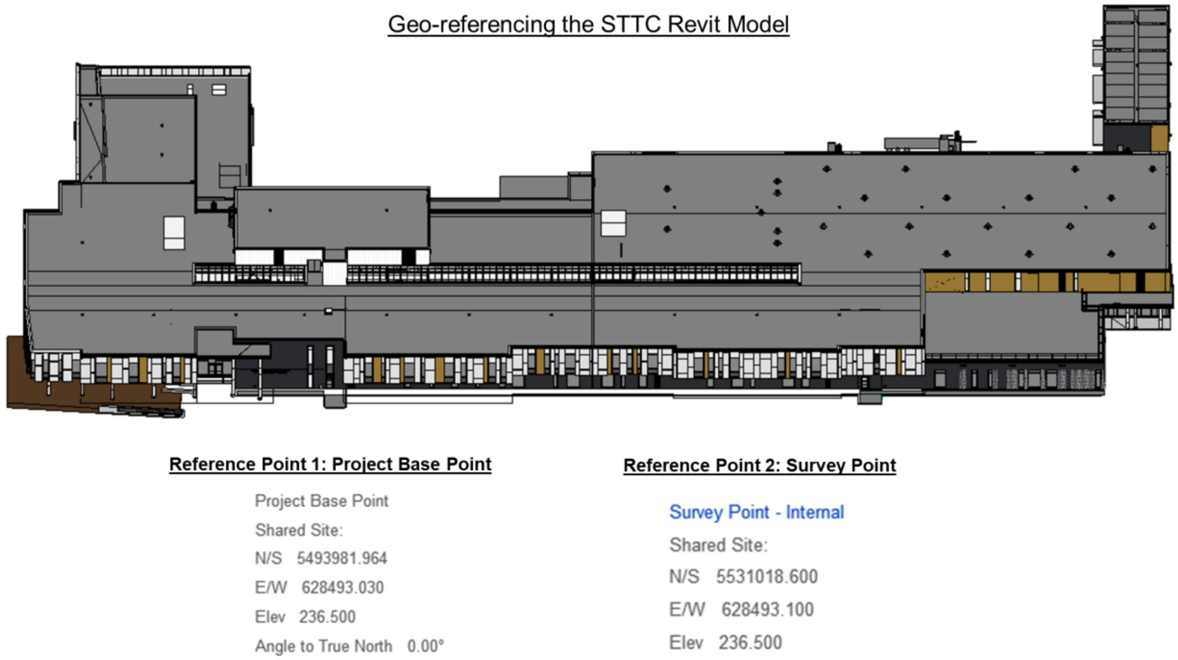


Figure 41: Geo-referencing of the STTC Revit model

Steps followed for curating the STTC Revit model for ArcGIS Pro import are as follows:

- Deleting and purging the elements and details that are not required (for example staircases)
- Geo-referencing the Revit model based on two reference points. The values of these reference points are taken from Google Earth for *WGS 1984 UTM Zone 14N* for Winnipeg, Manitoba.

Appendix V: Preparing STTC sensors' data for ArcGIS Pro integration

Indoor Thermostat Data

	A	B	C	D
1	SensorID	X_value	Y_value	Z_Value
2	Class M1	628586.7	5531036	243.331
3	Class M2	628592.9	5531036	243.331
4	Class R5	628599	5531036	243.331
5	Class C5	628604.7	5531036	243.331
6	Class R1	628610.7	5531036	243.331
7	Class R2	628616.8	5531036	243.331
8	Class R3	628623.1	5531036	243.331
9	Class R4	628629	5531036	243.331
10	Class C1	628635.7	5531036	243.331
11	Class C2	628641.5	5531036	243.331
12	Class C3	628647.9	5531036	243.331
13	Class C4	628653.6	5531036	243.331

Indoor Thermostat Locations
(For the area of interest)

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Time Stamp	Class M1	Class M2	Class R5	Class C5	Class R1	Class R2	Class R3	Class R4	Class C1	Class C2	Class C3	Class C4
2	2019-01-01 1:00	15.83	15.37	15.2	14.88	14.36	14.12	13.87	12.82	11.96	11.79	13.26	14.87
3	2019-01-01 2:00	15.7	15.23	15.05	14.73	14.19	13.93	13.7	12.64	11.78	11.6	13.06	14.7
4	2019-01-01 3:00	15.58	15.09	14.92	14.58	14.04	13.76	13.54	12.46	11.58	11.41	12.88	14.54
5	2019-01-01 4:00	15.47	14.97	14.79	14.45	13.87	13.59	13.38	12.28	11.41	11.23	12.7	14.39
6	2019-01-01 5:00	15.38	14.86	14.69	14.34	13.74	13.46	13.26	12.14	11.25	11.09	12.62	14.25
7	2019-01-01 6:00	15.27	14.76	14.58	14.22	13.61	13.3	13.12	12	11.1	10.94		14.13
8	2019-01-01 7:00	15.22	14.76	14.55	14.13	13.47	13.17	12.96	11.84	10.9	10.77		13.98
9	2019-01-01 8:00	15.26	14.85	14.56	14.1	13.38	13.05	12.87	11.73	10.79	10.66		13.91
10	2019-01-01 9:00	15.34	14.88	14.56	14.03	13.33	13	12.82	11.65	10.7	10.59		13.86
11	2019-01-01 10:00	15.38	14.96	14.6	14.03	13.48	13.24	12.98	11.77	11.2	10.72		14.11
12	2019-01-01 11:00	16.01	15.26	14.9	14.4	14.32	13.97	13.76	12.48	12.15	11.57		14.96
13	2019-01-01 12:00	16.65	15.66	15.35	14.8	15.1	14.43	14.33	13.31	12.99	12.41		15.94
14	2019-01-01 13:00	17.49	16.19	15.93	15.26	15.56	14.98	14.85	13.95	13.57	13.17		16.71
15	2019-01-01 14:00	17.7	16.7	16.54	15.71	16.01	15.56	15.33	14.58	14.12	13.91		17.4
16	2019-01-01 15:00	17.84	17.16	17.1	16.12	16.46	16.12	15.73	15.19	14.62	14.53		17.91
17	2019-01-01 16:00	17.71	17.3	17.33	16.31	16.58	16.28	15.89	15.15	14.71	14.35		17.94
18	2019-01-01 17:00	17.23	17.12	17.14	16.23	16.18	16.05	15.67	14.62	14.2	13.76		17.28
19	2019-01-01 18:00	16.85	16.78	16.75	16	15.72	15.74	15.29	14.18	13.65	13.29		16.7
20	2019-01-01 19:00	16.52	16.51	16.37	15.74	15.35	15.4	14.9	13.83	13.21	12.93		16.26
21	2019-01-01 20:00	16.31	16.2	16.08	15.52	15.07	15.11	14.59	13.54	12.85	12.63		15.89
22	2019-01-01 21:00	16.1	15.9	15.8	15.3	14.87	14.81	14.37	13.32	12.61	12.41		15.61
23	2019-01-01 22:00	15.9	15.61	15.49	15.04	14.66	14.54	14.15	13.11	12.38	12.21		15.36
24	2019-01-01 23:00	15.8	15.45	15.34	14.89	14.49	14.28	13.98	12.92	12.17	12.01		15.16
25	2019-01-02 0:00	15.7	15.36	15.27	14.76	14.35	14.12	13.83	12.77	11.99	11.85		14.98
26	2019-01-02 1:00	15.6	15.27	15.23	14.75	14.33	14.14	13.71	12.64	11.85	11.72		14.86
27	2019-01-02 2:00	15.53	15.19	15.09	14.6	14.16	13.92	13.75	12.63	11.78	11.66		14.76
28	2019-01-02 3:00	15.46	15.09	15.01	14.52	14.04	13.83	13.57	12.49	11.7	11.63		14.72

Indoor Thermostat Values
(Around 35000 rows of data)

Figure 42: Indoor thermostat locations and values

<u>Weather Station Data</u>

	A	B	C	D	E	F
1	Time Stamp	SensorID	X_Value	Y_Value	Z_Value	Temperature
2	2019-01-01 0:00	Weather50	628591.4961	5531051.036	250.754	-24.9
3	2019-01-01 1:00	Weather50	628591.4961	5531051.036	250.754	-25.15
4	2019-01-01 2:00	Weather50	628591.4961	5531051.036	250.754	-25.9
5	2019-01-01 3:00	Weather50	628591.4961	5531051.036	250.754	-26.275
6	2019-01-01 4:00	Weather50	628591.4961	5531051.036	250.754	-26.45
7	2019-01-01 5:00	Weather50	628591.4961	5531051.036	250.754	-26.3
8	2019-01-01 6:00	Weather50	628591.4961	5531051.036	250.754	-26.45
9	2019-01-01 7:00	Weather50	628591.4961	5531051.036	250.754	-26.3
10	2019-01-01 8:00	Weather50	628591.4961	5531051.036	250.754	-25.9
11	2019-01-01 9:00	Weather50	628591.4961	5531051.036	250.754	-24.375
12	2019-01-01 10:00	Weather50	628591.4961	5531051.036	250.754	-22.75
13	2019-01-01 11:00	Weather50	628591.4961	5531051.036	250.754	-21.56666667
14	2019-01-01 12:00	Weather50	628591.4961	5531051.036	250.754	-20.75
15	2019-01-01 13:00	Weather50	628591.4961	5531051.036	250.754	-19.625
16	2019-01-01 14:00	Weather50	628591.4961	5531051.036	250.754	-18.825
17	2019-01-01 15:00	Weather50	628591.4961	5531051.036	250.754	-18.825
18	2019-01-01 16:00	Weather50	628591.4961	5531051.036	250.754	-19.5
19	2019-01-01 17:00	Weather50	628591.4961	5531051.036	250.754	-19.3
20	2019-01-01 18:00	Weather50	628591.4961	5531051.036	250.754	-18.95
21	2019-01-01 19:00	Weather50	628591.4961	5531051.036	250.754	-18.6
22	2019-01-01 20:00	Weather50	628591.4961	5531051.036	250.754	-18.675
23	2019-01-01 21:00	Weather50	628591.4961	5531051.036	250.754	-18.575
24	2019-01-01 22:00	Weather50	628591.4961	5531051.036	250.754	-18.425
25	2019-01-01 23:00	Weather50	628591.4961	5531051.036	250.754	-18.25
26	2019-01-02 0:00	Weather50	628591.4961	5531051.036	250.754	-18.275
27	2019-01-02 1:00	Weather50	628591.4961	5531051.036	250.754	-18.075
28	2019-01-02 2:00	Weather50	628591.4961	5531051.036	250.754	-17.3

Weather station location and outdoor
temperature values
(Around 24000 rows of data)

Figure 43: Weather Station location and values

Appendix VI – Questions asked during survey and focus group interview

<u>Questions Specific to Group 1</u>

Q1. Describe the different types of information displayed in Image A (ArcGIS interface) for the purpose of visualizing indoor thermal comfort.

- Open ended question

Q2. Which is your preferred method to visualize/ obtain geometrical information for the classroom area?

- Choose between Image A or Image B

Q3. What do you prefer to visualize the indoor thermostat data associated with the classrooms?

- Choose between Image A or Image B

Q4. Which one of these platforms do you prefer to determine occupant thermal comfort?

- Choose between Image A or Image B

Q5. Which of the following methods would you prefer if you're visualizing indoor thermostat data for presentations/communications and decision-making?

- Choose between Image A or Image B

Q6. Overall, do you think that GIS Integrated digital twin will improve the visualization of various key performance indicators for Post Occupancy Evaluations?

- Very Likely
- Likely
- Neither Likely nor Unlikely
- Unlikely
- Very Unlikely

Q7. How would you rate your skills in using any kind of 3D software for BIM?

- Basic
- Intermediate
- Advanced

Q8. How would you rate your skills in using GIS software?

- Basic
- Intermediate
- Advanced

Q9. How would you rate your skills using excel for data analysis?

- Basic
- Intermediate
- Advanced

Questions Specific to Group 2

Q10. Have you ever used BIM or GIS to visualize building performance data?

Q11. What parameters do you look for while decision-making?

Q12. For designers, do you think visualizing building sensors data within a 3D space for the existing building will help make informed decisions for future purposes?

Q13. For facility managers, compared to the existing platforms, do you think GIS integrated digital twin approach will improve the visualization for certain indicators such as energy use and thermal comfort?

- Due to limitations in data collection, answer to this question has not been obtained.

<u>Questions for both Group 1 and Group 2</u>

Q14. How familiar are you with Digital Twins / Building Information Modeling (BIM)?

- Extremely Familiar
- Very Familiar
- Somewhat Familiar
- Not so Familiar
- Not at all Familiar

Q15. How familiar are you with Geographic Information Systems (GIS)?

- Extremely Familiar
- Very Familiar
- Somewhat Familiar
- Not so Familiar
- Not at all Familiar

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