LIVING LAB DIGITAL TWIN: CASE STUDY OF THE DEVELOPMENT OF A RESEARCH-ORIENTED DIGITAL TWIN IN A LEED PLATINUM ACADEMIC BUILDING

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ABSTRACT

Creating a living lab in a new academic building, to support diverse types of research projects, presents unique challenges that are rarely documented. Following the case study research method, we present the process and development of the datasets and the software platform created to enable faculty and students at a university to perform scientific studies that follow a living lab methodology. Although the motivation for the living lab project is sustainability, the intent is to have a domain-agnostic platform that can serve a variety of disciplines. The goal of this research is to support the development of theory regarding the continuous improvement of the built environment.

Keywords: living lab, digital twin, case study, sustainability, built environment.

1 INTRODUCTION

Digital twins of buildings have been developed for several reasons, including the validation or calibration of simulation results, fault detection and diagnostics, and performance monitoring and optimization. Although digital twins can be used exclusively with simulation, to assist in design, construction, or operations modeling, they would be fully leveraged when compared to a physical twin. At the scale of a large building, the instrumentation of the physical structure is an inherent part of the proper operations of the lighting, plumbing, fire safety, and mechanical systems. Beyond its use in building control systems, this physical infrastructure can benefit the development of a digital twin to support additional use cases.

A *living lab* is a research initiative that involves the deployment of various sensors and technology within a building, that could be conceptualized as a digital twin. The purpose is to create a real-world testing environment where researchers can design, develop, and run studies in areas related to building efficiency, occupancy, sustainability, user experience, and technology integration. This research environment has two key properties that make it a distinct methodology that can include a number of research methods, namely the context and the duration. First, living lab studies occur in an uncontrolled manner. Unlike a laboratory setting with controlled conditions, studies in a living lab do not have blocks of trials with counterbalancing of conditions for different subjects. The study context is intended to support the natural behavior of the participants. Second, living lab studies can be longitudinal but cannot rely on reexamining the same participants throughout. However, the uncontrolled study context allows for large numbers of repeated measures across multiple participants. Unlike other methodologies, living lab studies can, for example, help to establish common sequences of events, identify changes over time, and provide insight into cause-and-effect relationships, all in an unguided context.

Proc. of the 2025 Annual Modeling and Simulation Conference (ANNSIM'25)
May 26-29, 2025, Universidad Complutense de Madrid, Madrid, Spain
J.L. Risco-Martín, G. Rabadi, D. Cetinkaya, R. Cárdenas, S. Ferrero-Losada, and A. Bany Abdelnabi, eds.

While living lab research has been ongoing for several decades, few projects have focused on urban design and fewer still on architectural research questions. We believe this is due, in part, to the complexity of establishing a living lab platform for a building or campus. With this case study, we aim to formalize the process of developing living lab platforms in order to answer our research question on the ways that a living lab can contribute to the development of a theory of continuous improvement of the built environment.

2 RELATED WORK

We examine the related work from the areas of living labs and digital twins. We also touch on continuous improvement frameworks to motivate the need for a theory specific to the built environment.

2.1 Living Labs

The orginal conception and use of the term "Living Lab" is not clear, but is nicely summarized in the PhD dissertation of Dimitri Schuurman [1](pg. 143). The current American Living Lab notion is often credited to Georgia Tech [2], who used the term "Living Lab" for the design and construction of the Aware Home, a typical home on a street on campus which was instrumented with a number of sensors and in which novel technologies could be tested during everyday activities by residents. Generally, the term describes a research producing facility or environment that is, firstly, not a laboratory setting with controlled conditions, and second, is intended to be used for longitudinal studies and allows for large numbers of repeated measures. Unlike other methods, living lab studies can help to identify temporal properties such as the order and duration of activities or events, changes over time, and indicators of causation.

Since that time, the living lab concept has expanded to several disciplines studying real-life environments, including energy efficiency [3], human-building interaction (HBI) [4], smart cities [5], applied teaching in sustainability [6], mobility [7], assisted living [8], and healthcare [9]. Living labs as research infrastructures have been created internationally over the last two decades involving several stakeholders including researchers, students, companies, and citizens in a user-centered, iterative, open innovation ecosystem. The largest network of living labs is ENoLL [10], founded in 2006. The network comprises more than 470 living labs focusing on a wide range of research activities. According to Ballon [11], a living lab is "an experimentation environment in which technology is given shape in real-life contexts and in which end-users are considered co-producers".

Ståhlbröst [3] defines five Key Principles by which living labs should operate: Value, Openness, Realism, Influence, and Sustainability. The Value Principle includes both business-value and user-value. In our case, these are the same and includes users of the living lab service, such as faculty and students performing research. The Sustainability Principle refers both to the sustainability of the living lab and its responsibility to the wider community in which it operates. The innovation processes supported by a living lab must address sustainability issues, for instance, by reducing energy consumption, improving human health, or developing more efficient materials or designs. The Realism Principle captures one of the cornerstones of the living lab approach; that innovation activities should be carried out in a realistic, natural, real-life setting. The Openness Principle emphasizes that participants are aware that they are in an environment where multiple studies may be going on simultaneously. Controlled measures are not part of the living lab methodology and therefore users must be made aware of the situation.

One key aspect of the Influence Principle is to view users as active, competent partners and domain experts. This principle differs from related concepts such as participation, involvement, and engagement allowing for research methods such as Action Research that aims to simultaneously investigate and solve an issue. Participatory action research emphasizes that participants should be members of the community being studied, empowering those directly affected by the outcomes of the research. In this method, participants act as co-researchers, with their lived experiences considered formative to the research process. As the occupants of university buildings implicitly acknowledge the value of learning, universities are ideal environments for the implementation of a living lab. Nesti [12](p.6) states “Universities are important players, simply because they already have structures, technologies, and trained staff to implement Living Labs”, resulting in technological evaluations and improvements, enriched teaching and learning processes, and in providing business value for companies.

2.2 Digital Twins

The digital twin concept is often attributed to Grieves and Vickers [13] and, in the context of buildings, has grown to become integral to broader topics including living labs [14] and smart buildings [15]. Beginning in 2010, the convergence of low-cost sensors, Internet-of-Things (IoT), and cloud-computing, together with key technologies maturing, such as Revit, IFC, and time-series databases, lead to a number of publications that could now be considered to be digital twin works. In an office and cubicle context, works describing the representation and visualization of building performance data [16, 17, 18], and multi-sensor based occupancy detection to improve building efficiency [19] were published. In the context of facilities management (FM), [20, 21] explored how BIM can benefit FM processes. Occupancy detection and visualization research continued with Yang et al. [22] using heat maps showing occupancy trends.

Project Dasher, a long term digital twin research project at Autodesk Research, began in 2010 and concluded in 2023, as the productization of the research prototype began as Autodesk Tandem. Dasher was intended to be a building dashboard to serve as a visual debugger for buildings, to improve energy efficiency for environmental sustainability. The ongoing development of the project was primarily documented at the blog entitled "Through the Interface" authored by Kean Walmsley (https://www.keanw.com/). The project spawned other branches of investigation including digital twins at the campus scale [23] and going beyond occupancy presence detection toward activity recognition [24].

2.3 Continuous Improvement Frameworks

While many research methods emphasize generalization as the goal, an intrinsic case study emphasizes the uniqueness of the case to better inform holistic theory formulation [25]. In this work, the intent is to inform theory relating to continuous improvement of the built environment. Currently, continuous improvement frameworks and standards stem from manufacturing and quality improvement, for example, ISO 9001 Quality Management Systems. However, to move toward sustainability in the built environment, especially for retrofit projects, the authors believe a framework and theory specifically for buildings is needed and this work is intended to seed this theory development.

3 CASE DEFINITION AND SELECTION

The case study research method involves "defining the case, selecting the case(s), collecting and analyzing the data, interpreting data, and reporting the findings" [25]. In this work, we define the scope of the approach as a single building in a non-industrial urban context. The case selection was opportunistic and was motivated by the design and construction of a new computer science building on an academic campus in the south-western United States. The new 116,000 square-foot seven-story building, called is on the University Park Campus at the University of Southern California in Los Angeles. As significant sustainability goals were mandated for the building, being the first LEED Platinum building on the campus, the project was identified as a key learning opportunity for both faculty and students, driving the interest in developing a living lab. The temporal scope of the case begins with the project definition and goals, and ends with the initial recruitment of faculty members interested in using the living lab framework in their research. The period occurs over the entire calendar year of 2024.

3.1 Data Collection

Two data sets were collected to be combined as the basis of the digital twin; the Building Information Model (BIM) (see Figure 1) and the Building Automation System (BAS) elements.

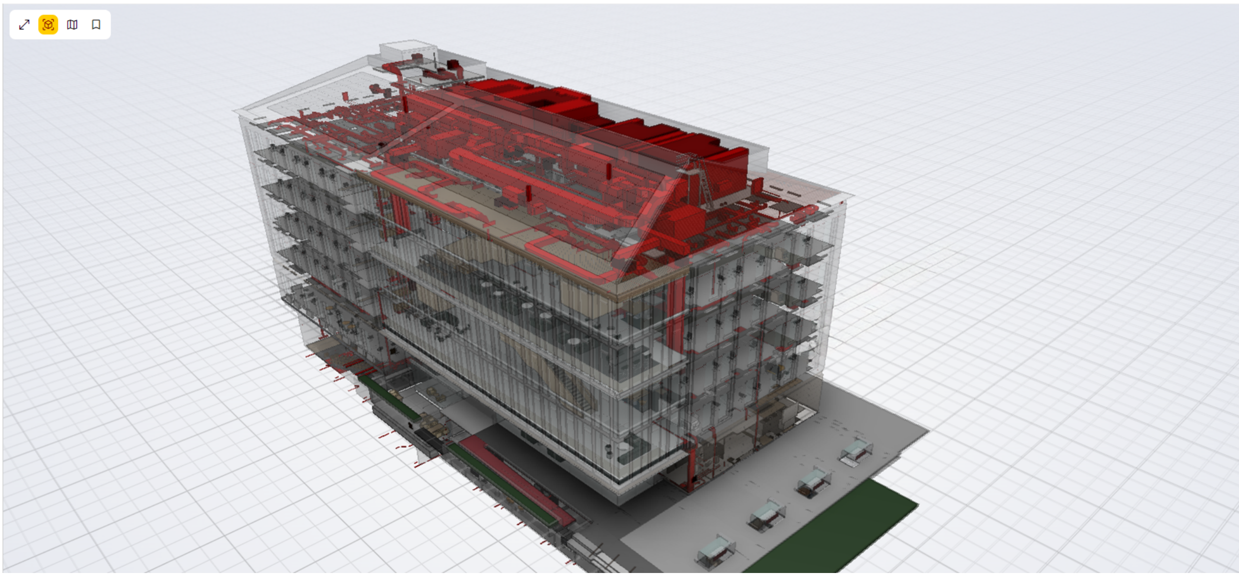

Figure 1: Living lab user interface to digital twin visualization of contextual 3D building information model.

The data collection process was quite involved and took approximately six months of coordination. First, to clarify the data sharing and ownership arrangement, documented permission from the architecture design firm and the mechanical design consultants was required. While the companies involved agreed quickly, the internal university facilities group further wanted signed agreements with the school of engineering and the specific faculty member leading the project. To accept collaborators from other institutions while controlling access and providing oversight, external users would be required to establish a formal agreement with the project leader. Throughout this period discussions were ongoing with the internal BAS facilities team, the BAS system supplier and their data security software group, together with our group. These discussions were to determine a workable solution to retrieve the data quickly and efficiently in a way that would not disrupt the normal operations of the building, yet make it available to the research community in a useful way. A critical aspect of this arrangement was the guarantee that living lab users would not have the ability to adversely effect the operation of the building systems. Delays in collecting these datasets were also caused by construction delays and by the time required for BAS setup and commissioning.

Three primary aspects of the datasets are relevant when creating a digital twin for a building. First, the BIM data should be simplified and organized to make corrections and for non-expert use. Second, the BAS schema and device data should be normalized into a database-like format. Third, the device (identifiers) IDs in the BAS dataset should be assigned to objects in the BIM dataset to spatially locate the devices and consequently the sensors within those devices.

For the BIM data, Autodesk Revit was used by the architecture firm to create the model (independent of this project, for their own purposes), and vendor-neutral Industry Foundation Classes (IFC) files were offered to us. However, we requested and received access to the source Revit files as it was unclear which IFC export settings would be needed. Also, it was not clear if multiple exports of different subsets of the model would be needed. This is important as living lab users are unlikely to be experienced in managing complex BIMs.

The BAS data originated from a Honeywell BAS that was centralized into the Honeywell Enterprise Buildings Integrator (EBI) campus-wide center. Again, coordination between the campus facilities group and the USC Viterbi School of Engineering information technology (IT) department was needed to bridge between the central data servers and a virtual server maintained by the IT department. After a number of discussions over several months, it was determined that an approach using the Open Platform Communications, Data Access (OPC DA) protocol standard would be viable, necessitating the use of the Matrikon OPC UA+DA Tunneller software. As the virtual server required occasional patches, on re-boot of the server, the system configuration would re-start the data logger we created to send the data to the Microsoft Azure Blob storage. We added a notification feature so we would be notified if data were no longer being sent to our cloud-based server.

3.2 Data Analysis and Interpretation

As Revit models are not standardized in how they are internally organized, it took two weeks to understand the model structure. Also, during this investigation, the export to IFC and import of model data was being performed using the `ifc.js` Javascript library. This process also involved correcting geometry that was appearing in unexpected ways. Finally, to prepare the model for the user interactions supported by our BIM viewer design, we spent a month to re-group objects and systems into logical groups based on the floor or subsystem, so that selection of these groups of geometry by the user would work as expected.

The BAS dataset included a number of aspects and properties and we processed these inputs to create a normalized list of device IDs, names, and associated sensor lists. This enabled the secondary process of mapping the device IDs into the correct objects in the BIM to spatially locate all of the devices. We were concerned that the device names and properties in the BIM would not correspond to the BAS information due to the fact that the BIM must be created before the BAS system can be defined, as well as the possibility of further differences introduced during the commissioning process. These concerns stem from the decoupling of the need to maintain a correspondence. While a full validation of this correspondence has not yet been performed, the mapping process was not as onerous as expected and this manual process took approximately one week. Some aspects of this task could be supported with improved tools and some level of automation.

4 IMPLEMENTATION

4.1 Secure Web Portal

To further enhance secure access to the dataset and to consolidate all available examples, a dedicated portal has been developed (see Figure 2). Researchers can authenticate through this portal to obtain individualized API tokens required for data access. The portal also serves as a centralized resource, hosting documentation, tutorials, and references in one convenient location. By combining security and accessibility, this web portal streamlines the workflow for academic and industry partners seeking to investigate building performance data.

4.2 BIM Viewer

Understanding the spatial context of sensor data is part of the sense-making process and is critical to ensure meaning correlations in space and time can be made in selected subsets of the data. To this end, we created a BIM viewer based on `three.js` with several tools to help users to assign devices in the model to device IDs in the BAS data, and to validate sensor locations. These include clipping plane and selection tools (see Figure 3).

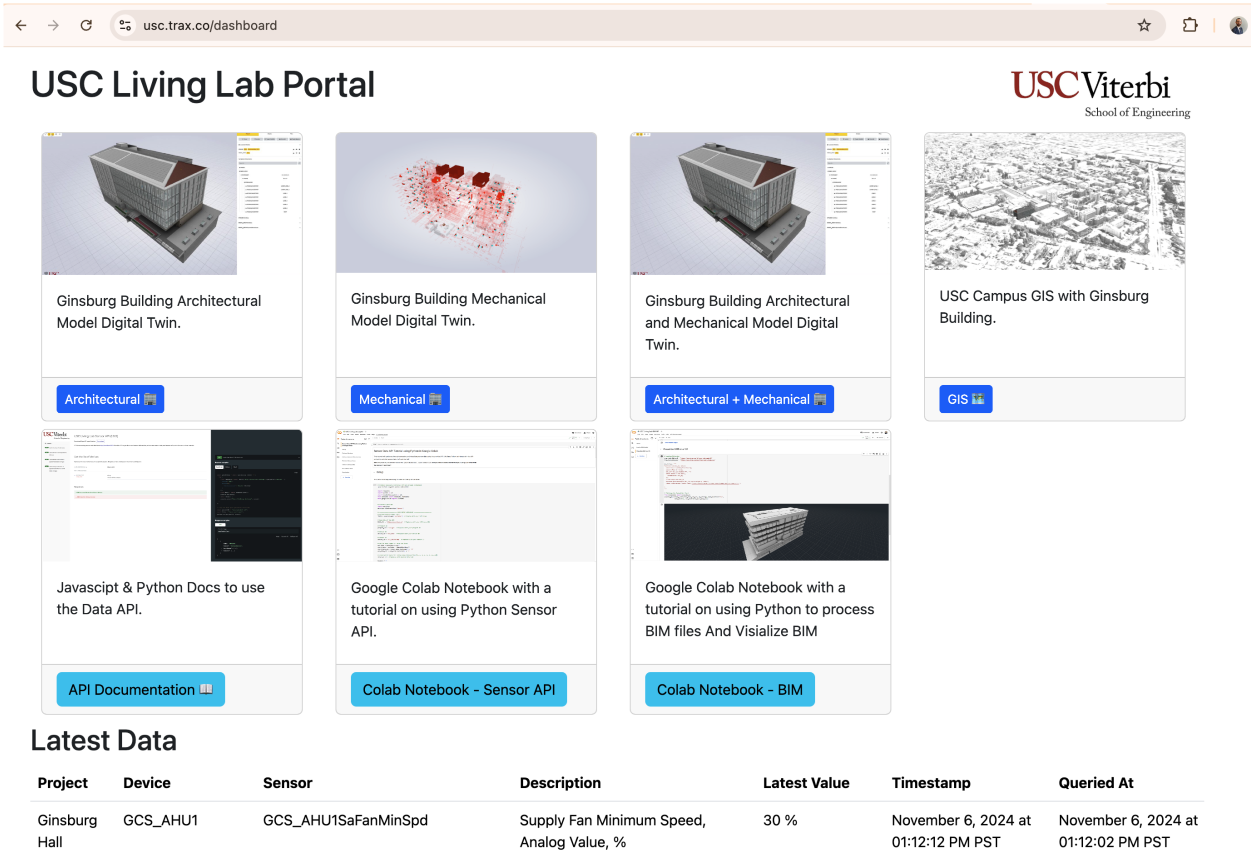

Figure 2: Living lab secure web portal for centralized access to models, APIs, and Colab Notebooks.

4.3 Data Acquisition and Logging

In order to continuously monitor building system performance, a data acquisition mechanism was developed to collect real-time sensor measurements from devices operating via Open Platform Communications, Data Access (OPC DA). A total of 252 devices—including Variable Air Volume (VAV) units—were manually tagged for inclusion, providing access to 3,114 distinct sensor points across the entire system. Sensor readings are pulled at ten-minute intervals, thus generating a comprehensive, fine-grained dataset suitable for time-series analysis. Following each collection cycle, the acquired data are automatically transferred to Microsoft Azure Blob Storage. To facilitate efficient retrieval and organization, all sensor measurements are stored in a hierarchical folder structure determined by time stamps. This structure accelerates query operations by reducing search overhead. Furthermore, an auxiliary cache table is continuously updated to store the latest sensor values, thereby enabling rapid access to near real-time data for visualization and preliminary analyses.

4.4 Roll-up Computations

To supplement the raw high-frequency data, a daily batch script is executed to generate roll-up statistics at multiple temporal resolutions (1-, 2-, 3-, 4-, 6-, 8-, 12-, and 24-hour intervals). For each specified interval, a range of statistical metrics—minimum, maximum, average, standard deviation, and sum—are computed. These roll-up metrics provide a more concise and high-level view of system performance over extended periods, facilitating trend analysis, anomaly detection, and comparative studies across different timescales.

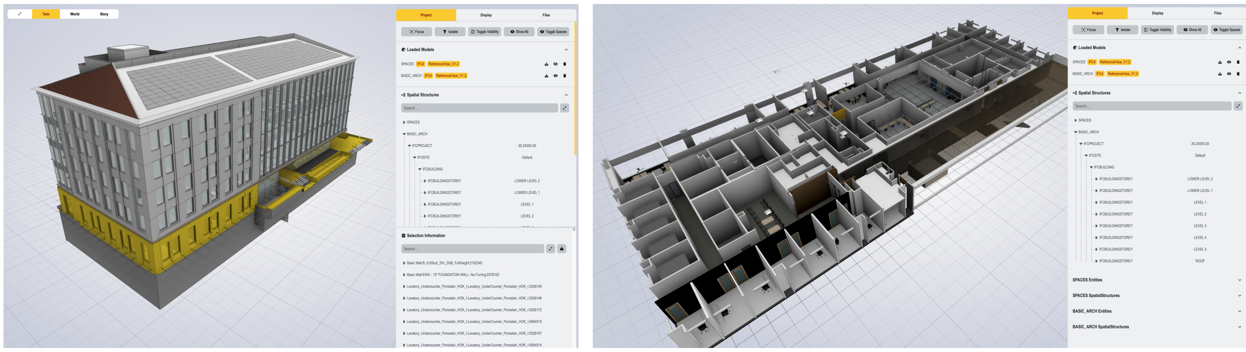

Figure 3: Living lab BIM viewer showing a selected floor (left) and isolating the view of that IFC data (right). The data panel on the right-hand side of each display shows the data hierarchy and the IFC properties.

4.5 Device and Sensor API

A RESTful Application Programming Interface (API) is provided to enable researchers and other stakeholders to query both device- and sensor-level metadata, as well as raw and aggregated sensor data. This API is comprehensively documented using an OpenAPI/Swagger schema, and the documentation is rendered via the Redoc library. Code snippets illustrating how to interact with the API are provided in multiple programming languages, including JavaScript, Python, and shell scripting, thereby lowering barriers to entry for a wide range of users. For example, in a Google Colab Notebook [26], users can retrieve the device list, sensors in a device, sensor data from a sensor, and plot the values (see Figure 4).

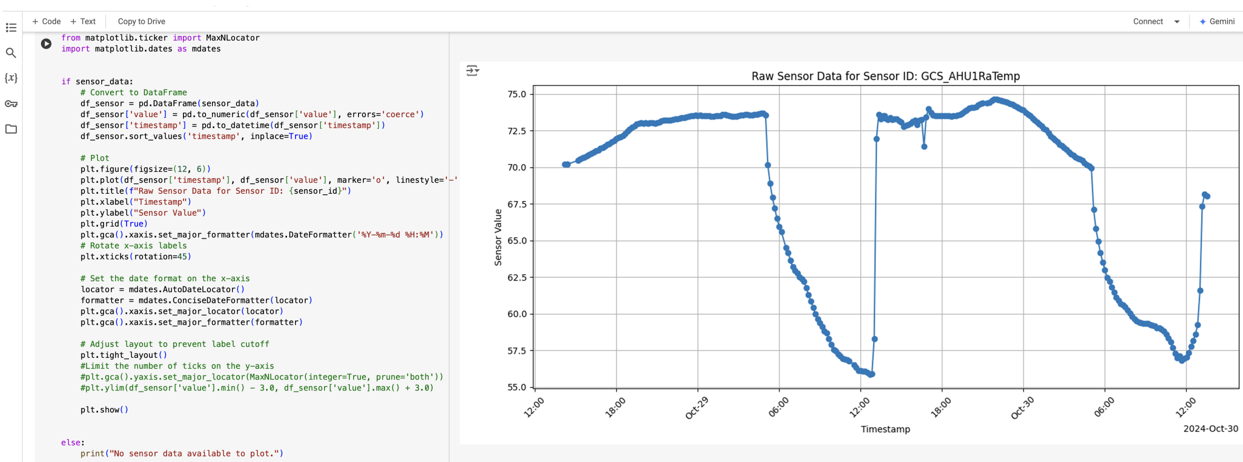

Figure 4: Retrieve and plot sensor data in Google Colab Notebook.

4.6 Colab Notebook Examples

Building upon the API documentation, a set of interactive Google Colab notebooks have been prepared to demonstrate how sensor data can be accessed, processed, and visualized. These notebooks use Python to retrieve sensor metadata, query raw time-series data, and request the aforementioned roll-up statistics via the RESTful API. In addition to basic data retrieval, the notebooks showcase methods for integrating Industry Foundation Classes (IFC) files. Researchers can extract IFC elements, visualize them in a 3D view directly within the notebook, and overlay sensor data within the 3D models (see Figure 5). This integrated approach allows sensor data to be contextualized according to spatial location, facilitating deeper insights into building performance, occupant comfort, and energy usage patterns.

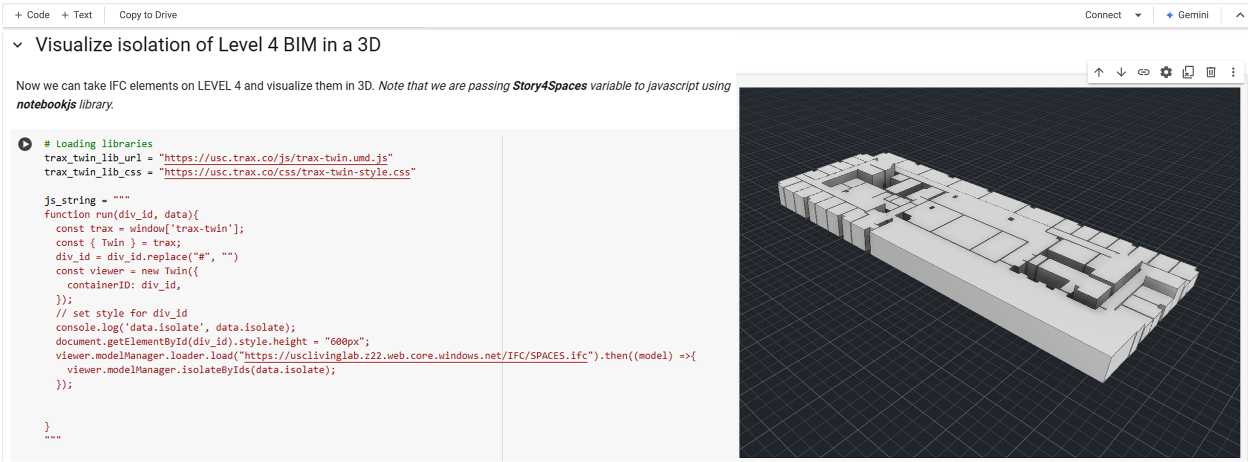

Figure 5: IFC model parts selection and display result in Google Colab Notebook.

By providing multiple points of entry, from direct REST API calls to comprehensive IFC-based 3D visualizations, this platform aims to support a wide range of simulation and analytical studies in architecture and urban design.

5 DISCUSSION AND FUTURE WORK

A key challenge in developing a living lab environment is the lack of standardization in both Building Information Modeling (BIM) and Building Automation Systems (BAS) datasets, as mentioned in Section 3.2. This issue means that similar projects will also have to spend considerable effort in data preparation. Future work should focus on the automation of data set normalization.

At the conclusion of the living lab platform development phase, the outreach process began. First, a webpage was published describing the project and inviting potential collaborators to apply to access the portal. Also, our team met with both the Computer Science and the Civil Engineering Departments in the School of Engineering. The system was introduced and collaboration projects were sought.

While several potential use cases were considered, one particular case was unforeseen but a good outcome for developing the platform. A large dataset had been collected for an occupancy study where anonymized WiFi connectivity data logs were collected for all the buildings on campus and the researchers asked to archive the past data in the living lab system and automate newly collected data to be sent to the living lab as well. To accommodate this request, an API was added to accept datasets and the investigation began on how to collect this type of data for the new building as well. This would expand the living lab scope to additional buildings on campus.

To fulfill one of the original goals of the project, to demonstrate the sustainability aspects of the new building, further work is planned to specifically isolate and visualize the rooftop solar cell installation. Also, an investigation is planned on what aspects of the LEED Platinum certification process could be automated using the existing building data being collected by the living lab project. Similarly, a comparison of the pre-construction energy modeling simulation results to the post-occupancy collected data, is also planned to be performed over the period of a full year.

6 CONCLUSION

This case study illustrates the development of a living lab digital twin in a LEED Platinum academic building, emphasizing its potential to support multi-disciplinary research. Like any investment in research infrastructure, research studies can leverage a living lab foundation for many years without additional funding requirements. By integrating existing sensor networks and a programmable software platform, the living lab supports studies that span sustainability, human-building interaction, and smart technology integration. Furthermore, the living lab methodology, with its focus on real-world, uncontrolled environments and longitudinal data collection, provides unique opportunities for researchers to explore natural behaviors, identify patterns, and advance theories of building performance and continuous improvement. This framework has the potential to inform theory construction through empirical grounding and evidence, hypothesis testing, explanatory power through visualization, and predictive power through simulation.

Although much has been accomplished to achieve the current level of fidelity, we expect that significant enhancements will be developed over the first year of deployment, and beyond. Future work will focus on expanding the platform's capabilities, increasing the benefit to collaborators, and exploring additional use cases to maximize its use in research and practice.

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