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PLANNING AND PROTOTYPING DIGITAL TWIN FOR EDUCATIONAL BUILDING

NAČRTOVANJE IN PROTOTIP DIGITALNEGA DVOJČKA IZOBRAŽEVALNI STAVBE

European Master in
Building Information Modelling

Master thesis No.:

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Izvleček:
Diplomsko delo raziskuje načrtovanje in izdelavo prototipov digitalnega dvojčka (DT) za izboljšanje energetske učinkovitosti in udobja uporabnikov v izobraževalni stavbi. Izbrani pristop združuje kvantitativne in kvalitativne metode in tehnične rešitve DT, ki se lahko uporabijo tudi v izobraževalne namene, s čimer bi želeli približati uporabo BIM in tehnologij digitalnih dvojčkov naslednjim generacijam. V nalogi je najprej podan podroben pregled literature opredeljeni so cilji za rabo DT, podporni scenariji uporabe in aplikacij DT ter možnosti uporabe meritev s senzorji IoT (angl. Internet of Things), ki so na voljo na trgu in izvedljivi za izbrani projekt.

Pri praktični implementaciji prototipa, je prikazano, kako se na podlagi zgodovinskih podatkov, zbranih podatkov o rabi energije in udobju uporabnika, lahko izdela načrt postavitve senzorjev, ki mu sledi ekonomska ocena predlagano tehničnih rešitev. Končni rezutlat teh korakov je prototip DT za izbrane scenarije. V fazi načrtovanja DT je bila izdelana strategija postavitve senzorjev z uporabo Dalux in fotografij 360°. Nato je bila izvedena ekonomska ocena predlaganih tehničnih rešitev ter prototip DT z uporabo Autodesk Tandem.V okviru naloge je bil izdelan tudi pristop za uporabo BIM in posnetek obstoječe stanja, ki je ključen pri izdelavi in implementaciji DT stavb. To delo je potencialno zanimivo zaradi poglobljene raziskave DT in postopka implementacije DT z BIM. Rezultati se lahko uporabijo v raziskovalne in izobraževalne name ter omogočajo pregled stavbe, njenega delovanja in tudi izboljšanje kakovosti bivanja.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

The thesis researches the planning and prototyping of a digital twin (DT) to improve energy efficiency and user comfort in an educational building. The chosen approach combines quantitative and qualitative methods and technical solutions of DT, which can also be used for educational purposes, with the aim of advancing BIM and DT technologies for the future.

The thesis provides a comprehensive literature review, the goals and objectives for the use of DT, supporting scenarios of use and applications of DT and investigation of indoor characteristics that can be measured by IoT (Internet of Things) sensors, which are available on the market and feasible for the selected project. In the DT planning phase, a sensor placement strategy was developed. It was based on historical data, collected data on energy consumption and occupancy patterns of spaces, and a survey using Dalux Environment to capture 360° photographs of the case study building. Following this, an economic evaluation of the proposed technical solutions was conducted. These steps led to the creation of a DT prototype adopted to the selected scenario, using Autodesk Tandem. In addition, the thesis outlines a systematic approach to the use of BIM and as-built modelling, which plays a crucial role in the development and implementation of building DTs.

This work is potentially interesting because of the in-depth research on DT and the process of implementing DT with BIM. The results can be used for research and educational purposes and enable the inspection of the building, its operation and also the improvement of well-being.

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I would like to express my gratitude to everyone who has been part of this academic journey. I've had the privilege of meeting incredible people who have supported me along the way. This year has been a tremendous learning experience, not just in the field of BIM but also in understanding various cultures. I've had the pleasure of exploring Arabic and Indian cuisine, delving into different languages, and challenging stereotypes. This program has truly expanded my horizons.

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AC – Air Conditioning

AEC – Architecture, Engineering and Construction

AECO – Architecture, Engineering, Construction and Operation

AI – Artificial Intelligence

ASHRAE – American Society of Heating, Refrigerating and Air Conditioning Engineers

BEP – BIM Execution Plan

BIM – Building Information Modelling

BMS – Building Management System

CMMS – Computerized Maintenance Management System

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

DIY – Do-it-yourself

DT – Digital Twin

HVAC – Heating, Ventilation, and Air Conditioning

IAQ – Indoor Air Quality

IFC – The Industry Foundation Classes

IoT – Internet of Things

LOD – Level of Development/Level of Detail

MEP – Mechanical, Electrical and Plumbing

ML –Machine Learning

MOSFET – Metal-oxide-semiconductor Field-effect Transistor

NDIR – Nondispersive Infrared

PIR – Passive Infrared

PRT – Platinum Resistance Thermometer

RH –Relative Humidity

t ° – Temperature

VOC – Volatile Organic Compounds

WWR – Window-to-wall ratio

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1 INTRODUCTION AND ELABORATION

The modern built environment is evolving at an unprecedented pace, driven by technological advances and the ever-increasing need for sustainable, comfortable and efficient spaces. In this dynamic context, the integration of digital technologies has emerged as a transformative force in the Architecture, Engineering, Construction and Operations (AECO) industry. Among these technologies, the concept of a DT has gained considerable prominence.

DT aims to integrate the strengths of different domains, including simulation, real-time monitoring, data analysis and optimization (Sharma et al., 2022). It represents a virtual counterpart of physical assets or systems, providing a comprehensive understanding of their real-time condition and performance. This technology has the potential to revolutionize the way we plan, design, construct and manage our built environment.

This master's thesis embarks on a journey to explore the profound impact of DT technology on educational buildings, focusing on two key aspects: improving user comfort and optimizing energy consumption. The underlying problem revolves around the question of how to strategically plan the development and implementation of a DT by leveraging pre-existing Building Information Modelling (BIM) models and available data. The resulting DT will serve as a powerful tool for monitoring and visualizing various aspects of a building, ultimately supporting informed decision-making in multiple scenarios.

Reduced student wellbeing and academic performance due to inadequate classroom conditions can lead to a decline in educational outcomes, with potential economic consequences for individuals and society as a whole (Toftum et al., 2015). This underlines the urgency of addressing the challenges facing educational buildings. In addition, increased sickness absence due to inadequate classroom ventilation could indirectly lead to reduced learning achievements (Toftum et al., 2015). As we delve deeper into the impact of DT technology on educational environments, we recognize its potential to address these critical issues and pave the way for improved learning environments.

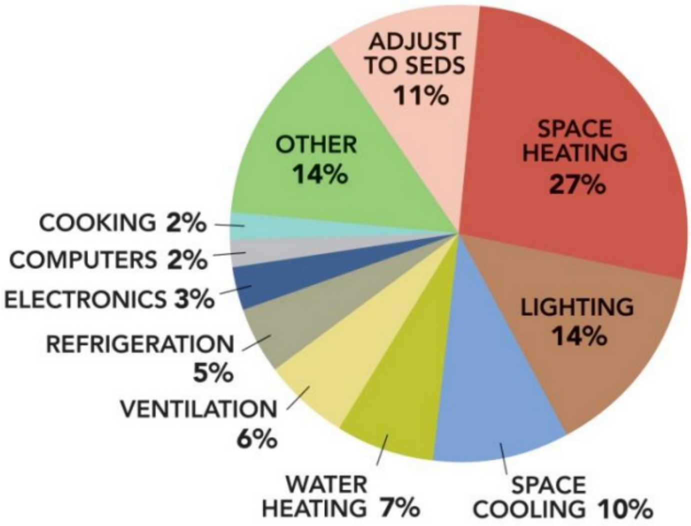


Figure 1. Energy consumption in commercial buildings by end users (Mayernik, 2012).

Furthermore, the end use of energy consumption in commercial buildings is a major concern, with space heating (27%), lighting (14%), space cooling (10%) and water heating (7%) being the main drivers as it is seen in Fig. 1 (Mayernik, 2012). As the major factors are all related to the actual use of buildings, the gap between the operation of a building and the actual needs of its occupants represents a potentially large opportunity for energy and water reduction. This underlines the urgent need for efficient resource use in educational buildings, a challenge that can be directly addressed to DT technology.

1.1 Problem Statement

The central problem addressed in this thesis is as follows: "How to plan the development and implementation of a DT by making use of a pre-existing BIM model and available data to monitor and visualize the conditions in the building in support of decision-making and various scenarios, e.g., building performance, use of buildings, well-being of the building users, and functioning of the building components."

1.2 Methodology

1.2.1 Research Design

This study will be conducted as a mixed-method research, combining quantitative and qualitative approaches to gather comprehensive insights into the impact of DT technology on educational buildings.

1.2.2 Data Collection

In literature review, a review and analysis of relevant literature on DT technology, DT applications and review of main indoor characteristics and related fields to provide a theoretical framework for the study will be done.

Secondly, an overview of DT solutions on the market such as software for DT implementation and a review of possible hardware will be conducted.

Finally, real-time data will be collected from sensors strategically placed in the educational building to monitor environmental conditions (e.g. t °, RH, CO_2 levels), occupancy patterns and energy consumption.

1.2.3 Data Analysis

Quantitative Data Analysis involves Data Exploration, which entails surveying historical data to gain insights into past trends, behaviors, and patterns. This process often includes creating visualizations such as time series plots and histograms to understand how variables have evolved over time. Additionally, Performing Regression Analysis is a key step in identifying relationships between environmental factors, and energy consumption. By exploring data, you can pinpoint potential relationships and questions for further analysis. Regression analysis, in turn, aids in predicting the impact of environmental conditions on energy usage.

Qualitative Data Analysis encompasses Theme Identification, which involves identifying themes related to various aspects, including energy optimization scenarios, user comfort scenarios, and the selection of different types of sensors or DT software solutions. Furthermore, Constant Comparison is a continuous process in which you consistently compare and refine your understanding of scenarios, hardware, and software options as you analyze more data and gather additional insights. This iterative approach empowers you to make well-informed decisions about the most suitable choices.

1.2.4 Planning DT

- Economic Analysis: Conduct a cost-benefit analysis to determine the economic feasibility of implementing DT technology in educational buildings. Compare the costs of installation and maintenance with the potential savings from energy efficiency improvements.
- Timeline: Create a detailed project timeline that includes milestones for data collection, DT prototype development, user feedback gathering, and economic analysis.

1.2.5 Prototyping DT

- Development of a prototype DT of an educational building based on Building Information Modelling (BIM) and sensor data with implementation of the selected DT technology usage scenario, choosing from such options as occupancy management, environmental monitoring or energy optimization.

- Evaluation and Validation: Establish performance metrics to evaluate the success of the DT prototype in improving user comfort and optimizing energy consumption.

1.2.6 Limitations

Acknowledge potential limitations associated with data collection, such as sensor accuracy or the inability to implement a particular scenario due to software limitations or the overall complexity of the task.

1.2.7 Conclusion

Summarize the findings, draw conclusions regarding the impact of DT technology on educational buildings, and provide recommendations for practical implementation.

2 LITERATURE REVIEW

This section explores potential scenarios for the use of DT technology in an educational building. The main focus is on reducing energy consumption and ensuring optimal comfort for end-users. In addition, standards of comfort and specifics of usage DT for Education Environment will be considered.

2.1 Digital transformation

Digital transformation in the AECO industry refers to the widespread adoption and integration of digital technologies, processes, and data-driven strategies across all phases of a building's lifecycle, from conceptualization and design to construction, operation, and maintenance. This transformation is driven by advances in technology and the recognition of the potential for enhanced collaboration, improved efficiency, reduced costs, and better outcomes in terms of project quality, sustainability, and overall performance (World Economic Forum, 2018).

At the core of this transformation are innovative technologies that are reshaping the way the AECO industry operates, including DT technology, the IoT and the principles of Industry 4.0.

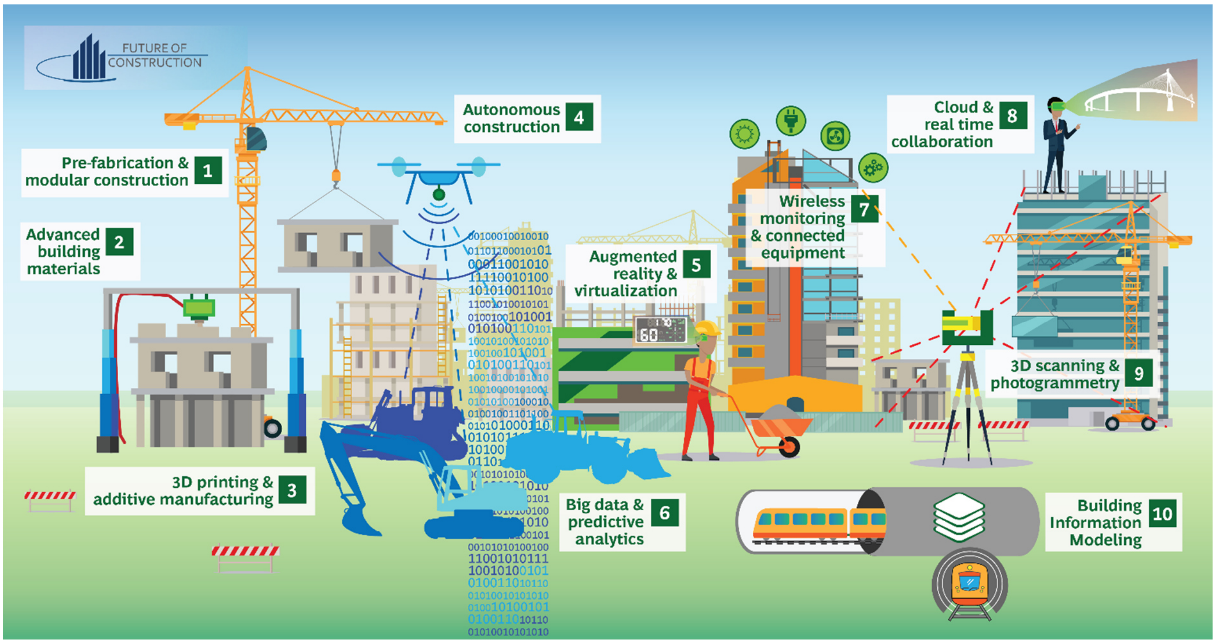


Figure 2. Future of Construction, (World Economic Forum, 2018)

2.1.1 Digital Twin

"Digital Twin (DT) refers to the virtual copy or model of any physical entity (physical twin) both of which are interconnected via exchange of data in real time. Conceptually, a DT mimics the state of its physical twin in real time and vice versa. Application of DT includes real-time

monitoring, designing/planning, optimization, maintenance, remote access, etc. Its implementation is expected to grow exponentially in the coming decades." (Singh et al., 2021).

The potential applications of DTs are many and varied depending on their intended use cases. Each DT configuration should cover specific information, tailored to the planned scenario (Singh et al., 2021). At its core, a DT consists of three fundamental elements: a physical entity, a representative model, and an interconnected interface (Fig. 3). This interface facilitates the exchange of data, information, and knowledge, supported by cutting-edge technologies such as computer vision, IoT, high-speed networks, and advanced analytic tools. It's worth clarifying that a DT goes beyond the limitations of a mere 3D model, as it uses data to accurately imitate real-world instances.

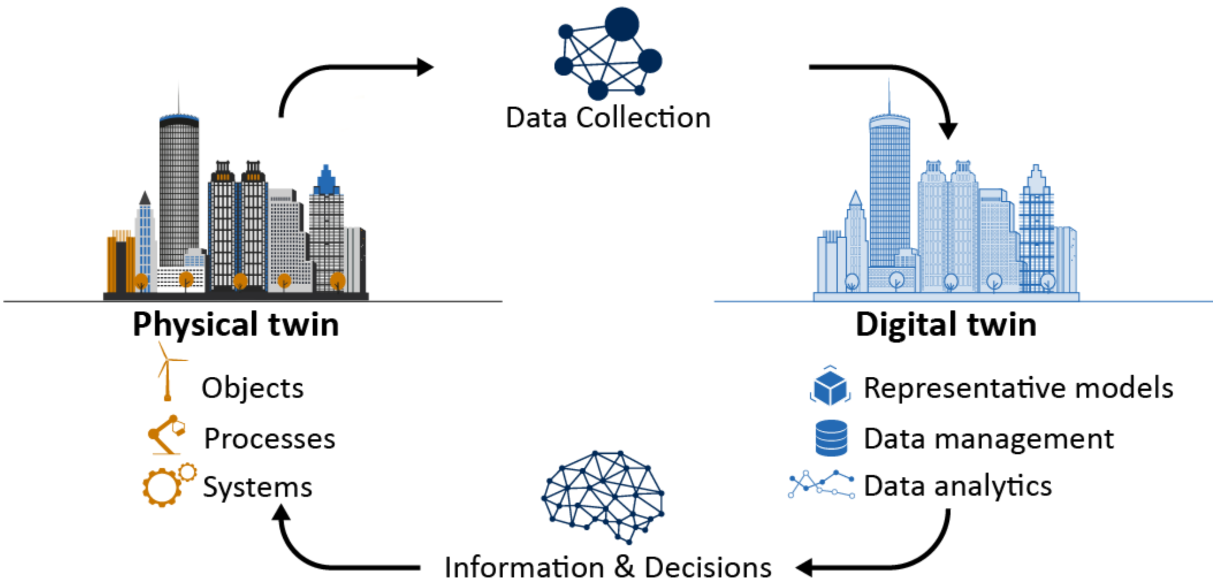


Figure 3. DT data flow, (LinkedIn, 2023)

Real-time data plays a key role in the functionality of DTs. However, their effectiveness depends on the automatic integration of data into the DT and the establishment of a bi-directional flow of data between the physical and digital parts (Singh et al., 2021). The appeal of DTs lies in their ability to enhance customer understanding, deliver unparalleled experiences, drive innovation, optimize operations and boost business evolution. This expanding popularity reflects their potential to enhance the resilience, sustainability and adaptability of the built environment.

Across a wide range of industries, DTs are being used in a variety of applications, including design, optimization, maintenance, safety, decision making, remote access and training (Singh et al., 2021; Javaid & Haleem, 2023).

At a mature level of DT technology, the dynamic nature of a DT will make it a continuously evolving digital/virtual model – that reflects the real-time state of its physical counterpart. This synchronization will be achieved through the continuous exchange of real-time data, accompanied by the preservation of historical data (Singh et al., 2021). It's important to note that changes in the DT will affect its physical twin, illustrating a mutual relationship that underscores their intrinsic connection.

2.1.2 Internet of Things

Figure 4. IoT. (Future of Privacy Forum, 2019)

The definition of IoT is: *"An open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data and resources, reacting and acting in face of situations and changes in the environment."* (Madakam et al., 2015).

The IoT is a transformative paradigm in which connectivity and communication play a central role. Within the IoT ecosystem, communication serves as the linchpin, enabling seamless interaction between disparate entities, including devices, sensor nodes, gateway units, and cloud servers, regardless of their geographic distribution.

A critical challenge that IoT addresses is the accessibility of data generated by sensors. Often, this data is not readily available to third-party applications. However, IoT overcomes this obstacle by establishing a well-defined data model that facilitates the exchange of information through an information and communication technology (ICT) infrastructure (Rinaldi et al., 2019). Recent technological advances have ushered in an era where internet-enabled sensors/devices, sophisticated electrical circuits and robust wireless communications are readily available. These advancements have broadened the horizons of IoT implementation, enabling its application not just in industrial environments but also in residential and commercial settings (Rafsanjani & Ghahramani, 2020)., thereby transforming the way online interactions occur across different sectors.

2.1.3 The concept of smart buildings

Figure 5. Concept of smart building. (HOBO Webinar, 2023)

In our context, the primary goal of implementing DT technology is to use data from sensors to enhance energy efficiency, sustainability, occupant comfort, and productivity while also making the building smarter (Fig. 5). To understand this concept better, let's delve into the notion of smart buildings.

A smart building is a building that utilizes advanced technologies and systems to optimize energy efficiency, enhance occupant comfort, and improve operational performance. It integrates various components, such as sensors, actuators, communication networks, and data analytics, to enable intelligent control and automation of building systems (Moreno et al., 2014).

Smart buildings leverage technologies like the IoT, Artificial Intelligence (AI), and data analytics to collect and analyze real-time data on energy consumption, occupancy, t °, and other parameters in highly interconnected way. This data is used to make informed decisions and optimize the operation of building systems, such as HVAC, lighting, security, and energy management (Moreno et al., 2014).

2.2 Developing Scenarios for DT of Educational Building

As the case study building is a university campus, only scenarios related to this type of building are considered. Thus, the main scenarios are divided into two main parts: scenarios for DT to optimize the environmental conditions according to the preferences of the end-users to improve health and productivity by understanding the behavior patterns of the occupants, and scenarios for DT to maximize the use of energy in the building, with the ideal state being a NZB (Talkhestani et al., 2019).

Regarding the case in question, the data collection from the building's sensors is implied. No data collection from smartphones or smart watches of building users is implied due to the complexity of data processing. Neither does it imply reconstruction or major retrofitting of the building.

2.2.1 Developing scenarios for DT for end-user welfare

1. **Occupancy management** since DTs can monitor real-time occupancy data within various campus facilities. Using this data, the allocation of study or work spaces, seating arrangements, and quiet zones can be optimized, based on analytics from occupancy sensors data. This ensures a conducive environment for learning and productivity because occupancy and actual use of spaces strongly affect the organizational effectiveness and functioning during the operational phase (Seghezzi et al., 2021).
2. **Real-time monitoring of environmental conditions** where DT can monitor and collect such conditions as air quality characteristics (t °, RH, CO_2, volatile organic compounds (VOC), etc.). The quality of air in an indoor environment is linked to the levels of concentration of people who spend a significant amount of time in the building as a worker, or student and customer (Fisk et al., 2002), as well as the spread of viruses within the context of coronavirus infection as an example (Elsaid & Ahmed, 2021) Hence, entities like companies, universities, and governmental institutions find it valuable to oversee the air quality in their buildings. Maintaining air quality beyond a specific threshold guarantees the safety and efficiency of staff, students, or customers. (Govindasamy et al., 2021).
3. **Adjusting of environmental conditions as a predictive maintenance** which can adjust HVAC systems and lighting to create optimal comfort. This contributes to the well-being of users by ensuring a comfortable working and studying environment by analyzing insights from historical data to develop strategies for improving system management (Govindasamy et al., 2021). And in general, by harnessing the power of ML and leveraging insights from professional engineers, we can effectively utilize DTs to proactively identify potential issues before they even arise, enabling us to forecast and mitigate future consequences (Javaid & Haleem, 2023).
4. **Emergency preparedness and safety** is an important research direction for realizing smart living environments with real-time monitoring, real-time interaction, and attempts to automate it (Liu et al., 2020). The DT can assist in emergency scenarios by providing real-time evacuation routes, safe assembly points, and instructions. This ensures the safety and peace of mind of users during critical situations.

5. **Navigation assistance** is crucial, particularly for newcomers who might find navigating a university campus overwhelming. A DT with integrated indoor navigation and a 360° Viewer (refer to Fig. 6) can offer real-time directions, highlight accessible pathways, provide estimated walking times, and pinpoint the locations of specific devices or equipment. By tracking the movements of both end-users and resources, it becomes feasible to enhance the overall convenience of services within the buildings (Jia et al., 2019).

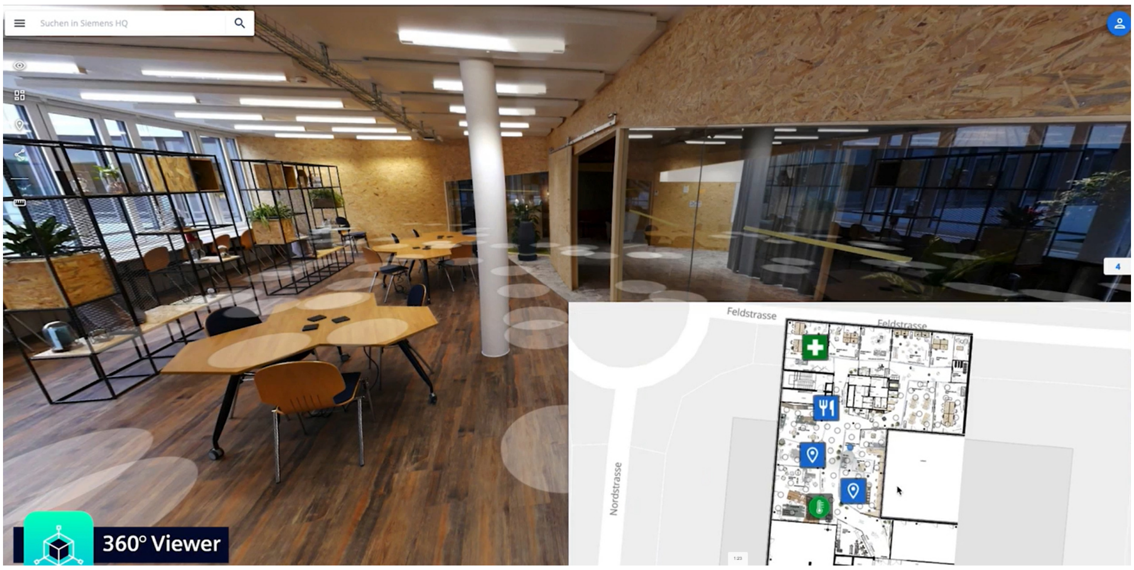


Figure 6. 360° Viewer. (Building X, Siemens, 2022)

2.2.2 Developing scenarios for DT to reduce energy consumption

1. **Building Energy Management** where DT is used for simulation and optimization of energy consumption in campus building. Monitor real-time data from sensors to identify areas of inefficiency and minimize downtime (Hosamo et al., 2022, Javaid & Haleem, 2023)., such as heating, cooling, lighting, and ventilation. Adjust settings virtually to find the most energy-efficient configurations before implementing changes in the physical environment.
2. **Occupancy and Space Utilization.** Use the DT to track occupancy in campus areas. By grasping space usage patterns, you can enhance heating, cooling, and lighting efficiency. Predict arrivals based on occupancy history, as seen in (Scott et al., 2011), to cut energy waste in less-used zones. Based on the comprehensive analysis of the impact of occupancy, behavior of end-users can effect building energy consumption up to 23.6 percent based on data from Azar & Menassa research, (2012).
3. **Water management.** Integrate water consumption data into the DT to analyze, plumbing, and water-related infrastructure. Identifying leaks or inefficient water usage

can lead to water and energy savings by installing smart water meters and reducing water pumping and treatment needs (Zekri et al., 2022).

4. **Lighting Management** presents an economical approach to diminishing energy consumption, carbon footprint, and operational expenses of existing buildings through the provision of effective control (Shen et al., 2014) over occupancy and lighting use through data collection and analysis using DT technology.
5. **Daylighting management** as part of Lighting Management, where the use of daylight coming into indoor areas is used more effectively, thus the use of on/off or dimmable lighting systems integrated with automated blinds, which can block direct sunlight and provide the design working level illuminance, and save energy (Shen et al., 2014). The example of fully integrated lighting and daylight control strategy is shown in Fig. 7.

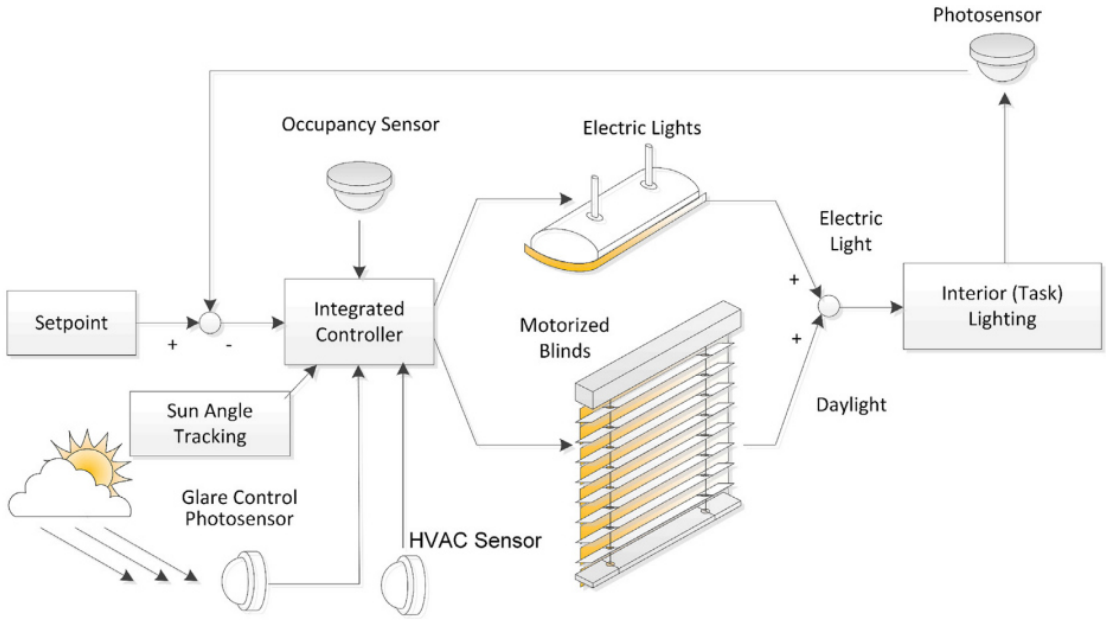


Figure 7. Fully integrated lighting and daylight control scenario. (Shen et al., 2014)

2.3 Indoor characteristics which is crucial to analyze

To enhance DT scenarios, IoT sensors should collect data on most relevant parameters such as t °, RH, CO_2 levels, occupancy, lighting, blind positions, and energy/water consumption, which can then be analyzed for potential enhancements.

2.3.1 Indoor Air Quality

Temperature (t °): controlling temperature in indoor areas is important for several reasons. Firstly, maintaining a comfortable temperature is crucial for occupant comfort and well-being. Extreme temperatures, whether too hot or too cold, can negatively impact productivity, concentration, and overall satisfaction (Dong et al., 2019).

In addition, temperature control plays a significant role in energy efficiency and cost savings. By optimizing temperature settings, energy consumption can be reduced, leading to lower utility bills and a smaller carbon footprint. Furthermore, temperature control is essential for preserving the integrity of sensitive equipment and materials. In certain environments, such as laboratories or data centers, maintaining a stable temperature is critical to prevent damage or malfunction of equipment.

Relative humidity (RH): maintaining humidity levels in indoor spaces is essential for various reasons. Firstly, it is crucial for ensuring occupant comfort and well-being. High humidity can lead to a sense of stickiness, discomfort, and difficulty in breathing, while low humidity can result in dry skin, irritated eyes, and respiratory issues (Farahani et al., 2014).

Secondly, humidity control is vital for preventing the growth of mold, mildew, and other harmful microorganisms. Excessive moisture in the air creates a favorable environment for these organisms, potentially causing health problems, allergies, and damage to building materials (Farahani et al., 2014).

Furthermore, humidity control plays a significant role in preserving the integrity of sensitive equipment and materials. High humidity levels can lead to corrosion, rust, and damage to electronics, whereas low humidity can result in the buildup of static electricity and harm delicate components (Farahani et al., 2014).

The definition of RH is: *"A ratio, expressed in percent, of the amount of atmospheric moisture present relative to the amount that would be present if the air were saturated. Since the latter amount is dependent on temperature, relative humidity is a function of both moisture content and temperature."* (National Weather Service, 2017)

Carbon dioxide (CO_2): a key marker of indoor air quality (IAQ) is carbon dioxide - a natural byproduct of human and animal respiration, decaying organic matter and the combustion of wood, carbohydrates and fossil fuels (HOBO Onset, 2017). Scientific research has shown that poor indoor air quality and elevated CO_2 levels are correlated with occupant discomfort and loss of productivity in various settings, including educational institutions (Toftum et al., 2015).

CO_2 is a trace pollutant that affects cognitive and respiratory function. Sustained concentrations around 600-700 ppm (parts per million) are normal (ASHRAE recommendations), 1000 ppm can cause mild cognitive impairment, increasing concentrations up to 2000-4000 ppm, indoor levels of CO_2 lead to the development of fatigue, headaches, drowsiness, poor concentration and loss of attention (Wikipedia, 2001).

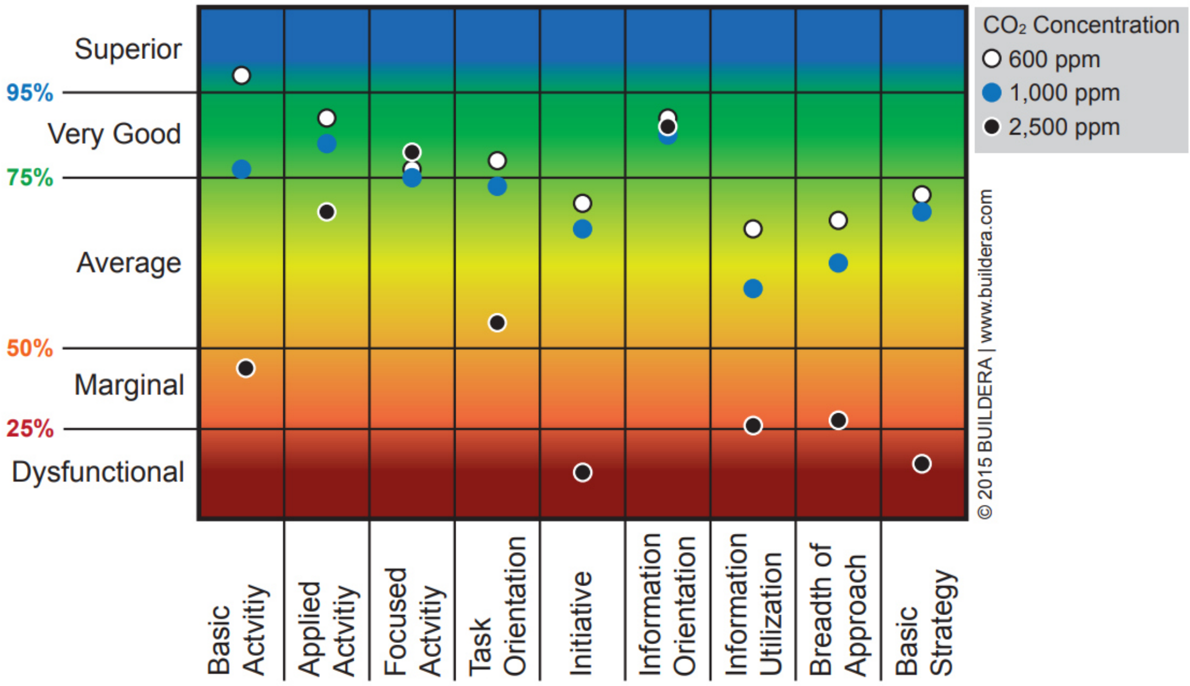


Figure 8. Impact of CO_2 On Human Decision Making Performance. (HOBO Onset, 2017)

2.3.2 Occupancy

Occupancy is an important characteristic because it provides crucial information about the actual use and functioning of a building or space. By integrating occupancy data into the DT, it becomes possible to accurately simulate and analyze the performance of the building in real-time. In addition, occupancy affects various aspects of building management, including energy consumption, HVAC operation, lighting control and space utilization. By incorporating occupancy data into the DT, it becomes possible to optimize these aspects and improve the overall performance of the building (Seghezzi et al., 2021).

Furthermore, occupancy data can be used to identify patterns and trends in space utilization which can inform decision-making processes during the operation and maintenance phase of a building. This information can be used to optimize space allocation, improve the user experience and increase the overall efficiency of the building (Seghezzi et al., 2021).

2.3.3 Lighting

According to a study by Mayernik (2012), lighting consumed approximately 14% of commercial building energy in the United States in 2010 (Fig. 1). Proper lighting design and control strategies can create a comfortable and productive visual environment and significantly reduce energy consumption, resulting in lower operating costs and a smaller carbon footprint.

In addition, lighting plays a critical role in visual comfort. Inadequate lighting can lead to eye strain, fatigue and reduced productivity, while excessive lighting can cause uncomfortable glare. By analyzing lighting levels, distribution and quality, appropriate lighting design and control strategies can be implemented to ensure optimal visual comfort for building occupants (Shen et al., 2014).

2.3.4 Opening/closing the blinds/windows

Effective control of blinds is crucial as it directly influences the ingress of natural light into a space, thereby impacting energy usage and visual comfort. The ability to manipulate blinds optimally enables the maximization of natural daylight, reducing the dependency on artificial lighting and consequently lowering energy consumption in buildings. Furthermore, blind control serves as a tool to manage glare and the intensity of direct sunlight entering a room, enhancing the comfort of its occupants. By implementing adept strategies for blind control, building inhabitants can enjoy the advantages of heightened energy efficiency, diminished reliance on artificial illumination, and an overall improvement in visual comfort (Shen et al., 2014).

2.3.5 Energy and water consumption

Collecting data from energy or water meters using intelligent data loggers is critical for several reasons. Firstly, it provides a comprehensive and accurate picture of energy and water consumption patterns within a facility. This data enables a deeper understanding of how resources are being used and can reveal valuable insights. Secondly, it enables the identification of trends, peaks and anomalies in consumption data. These patterns can indicate areas where energy use is particularly high or inefficient, signaling the need for further investigation and, in the case of water meters, can detect leaks or abnormal water usage in the building. Finally, smart data loggers make it easier to compare consumption data with industry benchmarks or similar facilities. This benchmarking process helps determine whether a facility's resource use is in line with expectations and industry standards, ultimately helping to identify areas for potential improvement and increased efficiency (U.S. Department of Energy, 2014).

3 OVERVIEW OF SOLUTIONS FOR DIGITAL TWIN

Two key components necessary for the development of a DT prototype are the software used to implement the desired scenarios and the IoT sensors for real-time data collection that allow comprehensive analysis.

3.1 Review of Software for DT

Numerous industries and companies are presently harnessing the power of DT platforms for their futuristic, reliable, efficient, cost-saving, and intelligent applications (Javaid & Haleem, 2023). Specifically, in the context of the scenarios proposed, the ability to read and process sensor data is crucial. Therefore, we will consider DT ecosystems that operate with the IoT, as they can facilitate data-driven decision-making.

3.1.1 Autodesk Tandem

Autodesk Tandem is an innovative platform that addresses the challenges of the entire building lifecycle, from design and construction to operation and maintenance. It leverages the power of DT technology, IoT integration, and Autodesk Forge to create a comprehensive solution for improved collaboration and **data-driven decision-making**.

Key Features and Benefits:

1. **DT Integration:** Tandem is at the forefront of the DT revolution, offering a platform where real-world building data and 3D models converge. This integration allows stakeholders to visualize and interact with the building's virtual counterpart, leading to better understanding and insights.
2. **IoT-Powered Insights:** By incorporating IoT data from sensors placed within the physical building environment, Tandem provides real-time insights into performance, occupancy, energy usage, and more. This data-driven approach enables predictive maintenance and informed operational decisions.
3. **Autodesk Forge Capabilities:** Tandem harnesses the capabilities of the Autodesk Forge platform, which includes APIs and tools for building customized applications. This empowers developers to extend Tandem's functionality, integrate diverse data sources, and create tailored solutions.
4. **Collaborative Facility Management:** Tandem serves as a collaborative hub for all stakeholders, from architects and engineers to facility managers and owners. Its user-friendly interface allows seamless sharing and updating of building information, ensuring everyone is on the same page.

5. **Visual Communication:** Visualization is key to effective communication. Tandem's visualizations of the DT facilitate clearer communication among stakeholders, regardless of their technical background.
6. **Lifecycle Optimization:** With Tandem, the benefits of BIM extend beyond construction into ongoing facility management. The platform aids in optimizing building performance, reducing downtime, and making informed decisions for upgrades and renovations.

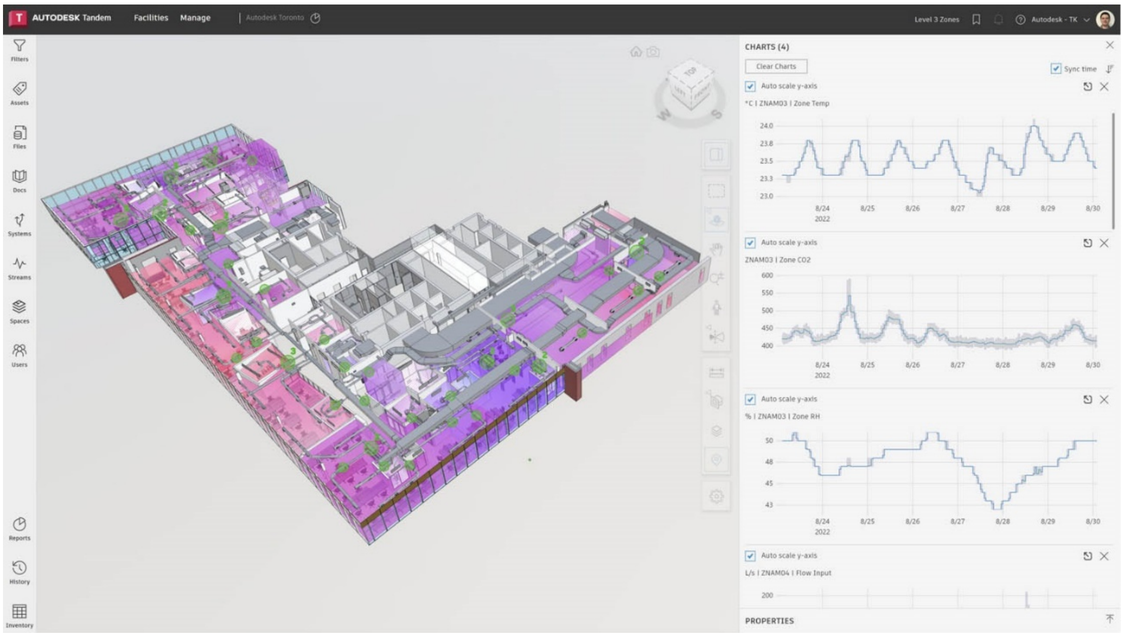


Figure 9. Heat maps of real time t °, RH, CO_2 levels. (Autodesk Tandem, 2021)

Tandem was the only one that has published pricing: 3,150 USD/Year including 10,000 assets, 2,000 streams and 3 years of time-series history. In the context of Autodesk Tandem, 'asset' refers to any item with a defined asset type and additional asset information linked through Autodesk Tandem. Streams' refers to the data collected from physical devices or sensors within Autodesk Tandem. These data points are collected at user-defined intervals and then stored for a pre-defined retention period, creating a historical time series record. (Autodesk Tandem, 2021).

3.1.2 Dalux Field

Dalux Field is a cutting-edge software platform that transforms building management by seamlessly integrating IoT capabilities and DT technology. This comprehensive solution offers a range of features designed to enhance collaboration, optimize operations, and empower stakeholders throughout the entire building lifecycle.

Key Features and Benefits:

1. **Digital Twin Advancements:** Dalux Field harnesses the power of DT technology to create dynamic virtual replicas of physical buildings. This integration enables stakeholders to interact with a visual and data-rich representation of the building, facilitating better decision-making and insights.
2. **IoT-Driven Insights:** By integrating data from IoT sensors strategically positioned within the building's infrastructure, Dalux Field provides real-time insights into crucial aspects such as energy consumption, occupancy trends, and equipment performance. This data-centric approach empowers proactive maintenance and data-informed strategies.
3. **Collaborative Workflows:** Dalux Field fosters seamless collaboration among stakeholders by offering a centralized platform for sharing and updating building information. Architects, engineers, contractors, and facility managers can collectively contribute and access pertinent data, streamlining communication and minimizing errors.
4. **Visual Representation:** Visualizations play a pivotal role in conveying complex information effectively. Dalux's visual interpretations of the DT facilitate communication and comprehension across diverse teams, regardless of their technical backgrounds.

Figure 10. Dalux Field Interactive 2D and 3D Visualization

5. **Operational Excellence:** Beyond the construction phase, Dalux Field continues to support ongoing facility management, aiding in maintenance, renovations, and performance optimizations. The platform empowers efficient resource allocation and informed decision-making for sustained building performance.

3.1.3 EcoDomus (Siemens Smart Infrastructure)

Siemens Smart Infrastructure has acquired EcoDomus' DT software for buildings, expanding its digital building portfolio. The software creates and visualizes BIM-based digital building twins, integrating BIM, BMS, CMMS, and IoT systems. This enables BIM-driven workflows, real-time monitoring through IoT sensors, and enhanced insights for building operations and maintenance. The software focuses on utilizing BIM benefits beyond construction, improving efficiency in the operations and maintenance phase and offering customers optimized building performance, cost reduction, and sustainability (Siemens Smart Infrastructure, 2021).

3.1.4 Nexus Twin

Nexus Twin is a powerful WEB cloud-based DT solution that excels in IoT integration. It offers secure data access through any browser, making it convenient for users to access information anytime, anywhere.

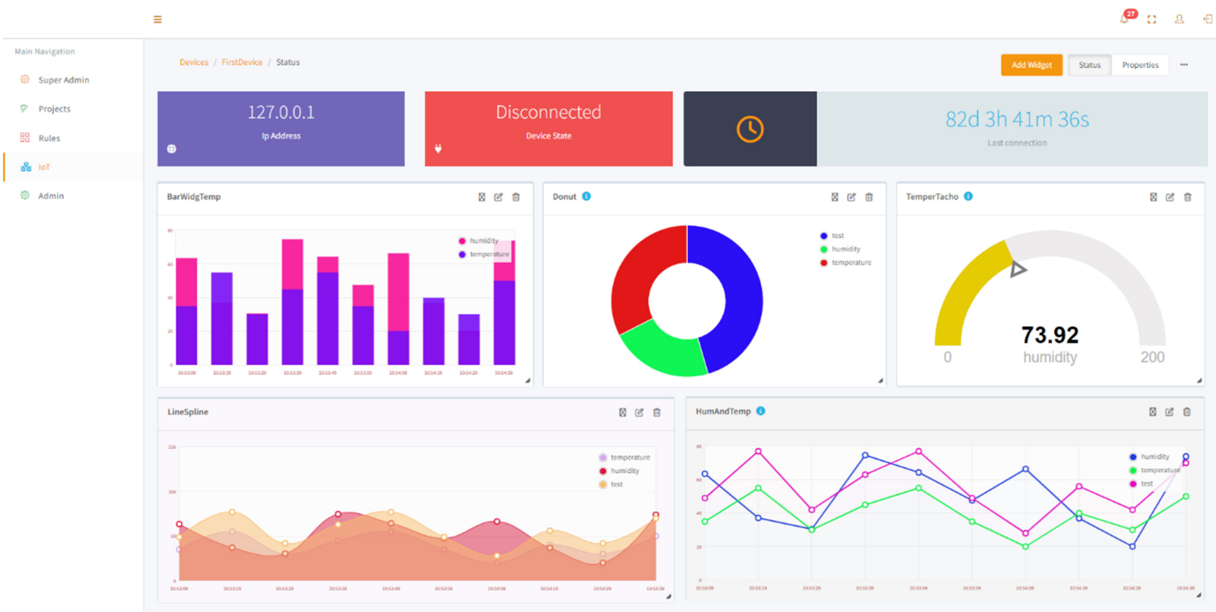


Figure 11. Main navigation page (Nexus Twin, 2022).

The software efficiently manages extensive datasets, including BIM, GIS, and IoT data. It starts with uploading open BIM .ifc files from various asset disciplines, creating a centralized federated model. This enables collaborative work among stakeholders in different asset lifecycle phases.

Key project metrics and operational insights are available through dashboards and model calculations. Users can navigate, inspect, and search BIM models with built-in tools, including conversational Open AI filters (Nexus Twin, 2022).

3.1.5 Smart Building Cloud platforms

Although these applications are not full blown DT software, they are discussed as an example of sensor reading capability platforms:

HOBOconnect Monitoring App: The application seamlessly integrates with HOBO MX Series data loggers, enabling efficient data collection through Bluetooth connectivity within proximity. It empowers users to effortlessly monitor real-time conditions without the necessity of a direct connection, thus saving valuable time with the convenience of bulk data downloads. Furthermore, it promotes enhanced collaboration by facilitating data sharing via text and email, and offers versatile export options, including CSV, XLSX, for streamlined data management and analysis.
Price for subscription: free of charge with the purchase of HOBO MX Series data loggers.

Abound by Carrier: Abound is a cutting-edge Smart Building Cloud application that serves as a comprehensive digital platform, offering a unified perspective on data across your entire building portfolio. By seamlessly connecting to all your existing building systems, equipment, and sensors through open protocols, Abound transforms raw data into actionable insights, empowering you to enhance building efficiency, comfort, and sustainability (Fig. 12).

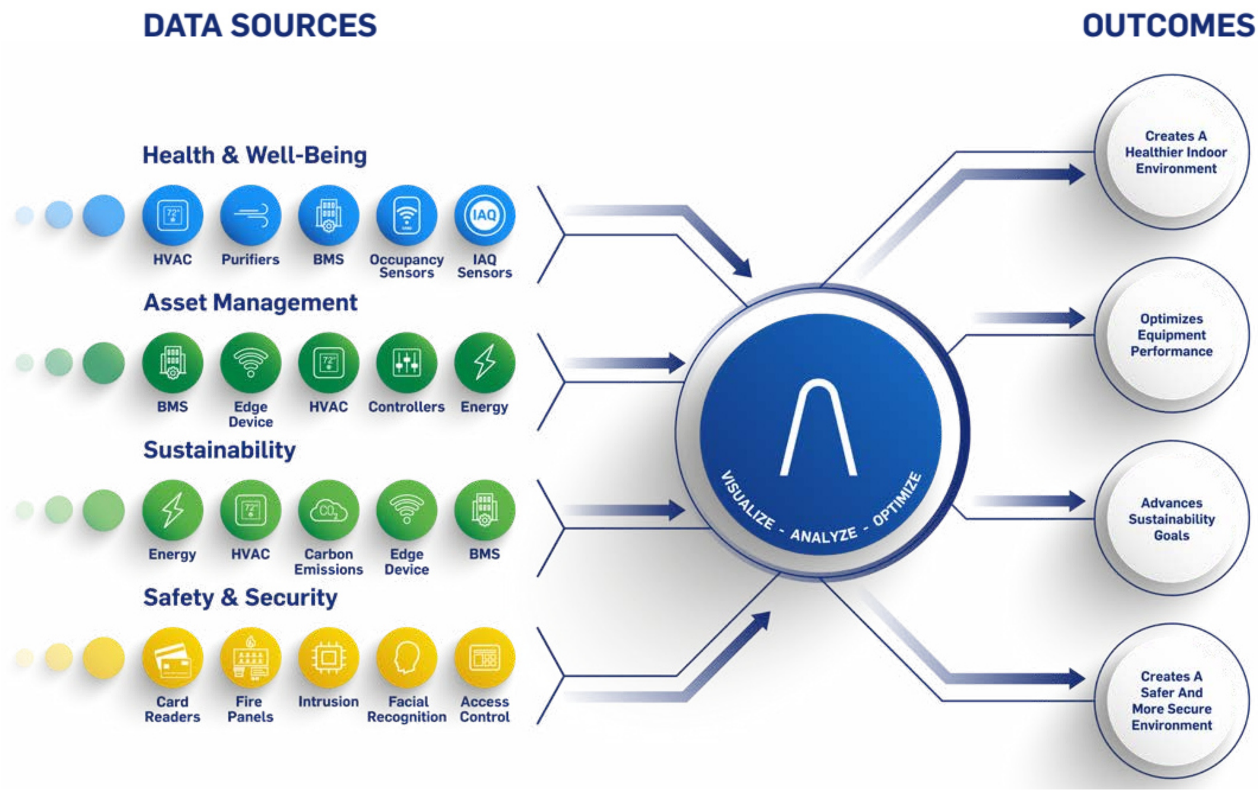


Figure 12. Outcomes of the platform (Abound by Carrier, 2021)

This innovative solution not only gathers performance data from diverse sources to establish a singular source of truth for informed decision-making but also ensures occupant confidence in indoor environmental safety. With its intuitive interface, Abound provides a clear view of all building systems within your portfolio, efficiently merging disparate data and swiftly identifying anomalies in real-time for rapid issue resolution.

Siemens Building X: Siemens Building X is a versatile platform that streamlines building operations for enhanced user experiences, improved performance, and sustainability. It offers user-specific apps, like Building X AI-enabled tools, for efficient data-driven decision-making:

- The Energy Manager tracks energy use, costs, and emissions, aiding sustainability goals;
- The Security Manager automates security workflows, ensuring proactive incident management;
- The Operations Manager provides real-time asset monitoring, minimizing downtime and enhancing business continuity;
- The 360° Viewer offers a holistic view of buildings through virtual 3D environments and intuitive indoor navigation, aiding in equipment management and spatial understanding.

3.2 Review of Hardware

The integration of advanced sensors and data loggers is becoming a key component of modern building management (Fig. 13). These technologies provide crucial insight into aspects such as building performance, safety and cost-effectiveness, while also facilitating the refinement of energy demand forecasts and the optimization of building and en operations (Hayat et al., 2019).

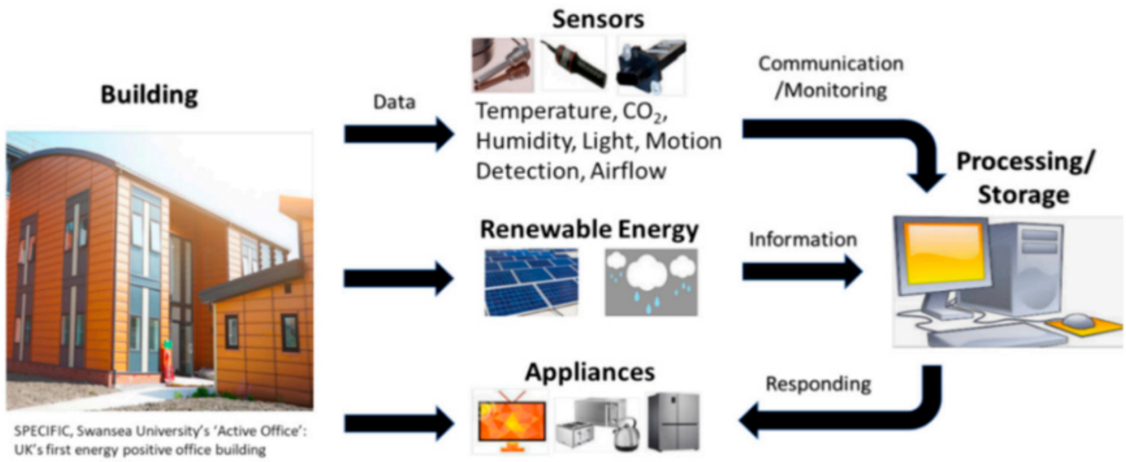


Figure 13. Overview of building management (Hayat et al., 2019)

Various aspects affecting the choice of sensing and metering solutions will be explored. The essential factors include:

- *"Accuracy;*
- *Ease of deployment;*
- *Communication protocol;*
- *Granularity;*
- *Cost;*
- *Availability."* (Hayat et al., 2019)

3.2.1 Generic types of sensors

1. **Sensor types:** A variety of sensor types allows the most appropriate sensor to be selected for a particular application based on factors such as measurement range, accuracy, response time, power consumption and cost. This ensures that measurements are accurate and reliable for the intended purpose. Based on the research conducted by Ahmad et al. (2016), Tab. 1 has been prepared with the main types of sensors.

Table 1.Type of sensors with their main characteristics (Ahmad et al., 2016).

Measured parameter	Type of sensor	Accuracy/Range	Response time	Communiation	Approx. price, (US$)	Measuring range
Room temperature	Thermistor	±0.1–0.5 °C	10–30 s	Wireless Wired	20–70	−50 to 180 °C
	Thermocouple	±0.8–4 °C	10–80 s	Wired Portable	10–50	−100 to 300 °C
	PRT	±0.25–0.6 °C	3–8 min	Wireless Wired	35–100	−50 to 100 °C
Relative humidity	Capillary thermostat	-	5–12 min	Closed control	20–60	−35 to 65 °C 0–100% RH
	Capacitive polymer	±2–4.5% RH	10–50 s	Wireless Wired	50–200	−35 to 65 °C 0–100% RH
	Ceramic resistance	±2–5% RH	10–50 s	Wireless Wired	40–150	10–90% RH
CO_2 concentration	NDIR	±30–80 ppm	30–50 s	Wireless Wired	200–500	0–2000 ppm
CO and VOC concentration	MOSFET	±50–100 ppm	<60 s	Wireless Wired Portable	200–500	400–2000 ppm CO_2 eq.
Occupancy	PIR	3–5 m radius or 5–12 m front and 3–8 m lateral	10 s–15 min	Wireless Wired Standalone	25–80	-
	Ultrasonic	185 m²	30 s–30 min	Wireless Wired Standalone	150–300	-
Light	Photo-diode	±8–10% of illum.	N/A	Wireless Wired Standalone	50–150	-
	Photo-sensor	±8–10% of illum.	N/A	Wireless Wired Standalone	100–250	-

2. **Network technologies:** A network refers to the infrastructure or system that enables devices to connect and communicate with each other. It encompasses the physical components, such as routers, switches, and cables, as well as the logical organization and configuration of these components. Networks can be classified based on their geographical coverage, such as local area networks (LANs), wide area networks (WANs), or personal area networks (PANs) (Kurose & Ross, 2017).

   On the other hand, communication protocols are a set of rules and standards that govern how data is transmitted, received, and interpreted between devices in a network. They define the format, timing, and sequence of data packets, as well as the error detection and correction mechanisms. Communication protocols ensure that devices can understand and interpret the data exchanged between them, enabling effective communication (Stallings, 2013).

   So, networks provide the physical infrastructure for devices to connect and communicate, while communication protocols define the rules and standards for data transmission and interpretation within a network.

3. **Communication protocols:** The choice of IoT protocols for a DT implementation depends on the specific requirements, constraints, and objectives of the project. It's essential to assess factors like data volume, latency tolerance, device constraints, and security considerations when selecting the most appropriate protocols to ensure seamless integration and communication within the DT ecosystem. Some commonly used protocols include:

   1. **Wi-Fi:** Wi-Fi is a widely used wireless communication protocol that provides high-speed data transmission over short to medium distances. It is suitable for applications where high bandwidth and internet connectivity are required.
   2. **Bluetooth:** Bluetooth is a short-range wireless communication protocol that is commonly used for connecting devices in close proximity. It is suitable for applications that require low power consumption and low data rates, such as wearable devices and smart home applications (Al-Sarawi et al., 2017).
   3. **Zigbee:** Zigbee is a low-power wireless communication protocol designed for low data rate, low-cost, and low-power applications. It is commonly used in home automation, industrial monitoring, and control systems (Al-Sarawi et al., 2017).
   4. **Z-Wave:** Z-Wave is a wireless communication protocol designed for smart home and building automation systems. Operating in the sub-1GHz frequency

band, Z-Wave offers exceptional range and penetration through walls, making it ideal for larger buildings. Z-Wave is renowned for its strong focus on interoperability, as all devices must pass rigorous certification to ensure compatibility across different manufacturers' products (Hayat et al., 2019).

5. **LoRaWAN:** LoRaWAN (Long Range Wide Area Network) is a low-power, wide-area network protocol that enables long-range communication with low data rates. It is suitable for applications that require long-range connectivity, such as smart city infrastructure and agricultural monitoring (Al-Sarawi et al., 2017).
6. **BACnet:** (Building Automation and Control Network) is a widely used communication protocol in the field of building automation. It is an open, vendor-neutral protocol that allows different building automation devices and systems to communicate and exchange data with each other (Hayat et al., 2019).

3.2.2 Specific types of sensors

In the context of this thesis, the selection of IoT sensors and data loggers was carefully considered to meet the specific requirements of the educational building characteristics outlined in subchapter 2.3. After a thorough evaluation, the data loggers provided by Onset HOBO were selected. This decision was based on the unique attributes of the Onset HOBO offering, in particular the seamless cloud connectivity between the data loggers and the HOBOlink Remote Monitoring browser page, which facilitates efficient data storage and upload from the data loggers. Notably, such comprehensive solutions with cloud integration are relatively rare in the IoT sensor market. Many companies that produce sensors or Smart building cloud platforms fail to provide solutions as robust and effective as those offered by Onset HOBO because there are many principles of communication between the data logger and the database, and at least it is not possible to take any sensor manufacturer and implement it in the Onset HOBO system but the most important point when it comes to using sensors is the ease of integration and collecting data from them in real time. The choice was also influenced by the positive experiences of university staff who had previously worked with this manufacturer.

Data loggers and sensors such as smart thermostats, open/close loggers, VOC sensors and water leak sensors won't be considered when planning a DT. This is because the HOBO manufacturer doesn't offer solutions for these specific types of measurements. However, they will be considered as examples of possible solutions.

Onset's Bluetooth-enabled HOBO MX1100 series data loggers will be reviewed firstly, since they allow to monitor a wide range of indoor conditions, including t °, RH, CO_2, light intensity, and more - making data collection more accessible due to:

- Convenient wireless setup and easy data offload via Bluetooth technology;
- Highly accurate measurements and large memory;
- Easy to deploy and offload using free HOBOconnect app;
- Option to add the MX Gateway for near real-time, remote access to data in HOBOlink cloud software;
- Patented connectivity technology.

1. HOBO Carbon Dioxide/Temp/RH Data Logger – MX1102A

Figure 14. Data logger MX1102A (HOBO Onset, 2019)

Main characteristics of MX1102A:

1. Visual and audible high & low alarm thresholds;
2. Self-calibrating NDIR CO_2 sensor technology ensures optimal accuracy and lower maintenance costs;
3. Mount technology: Wireless;
4. Range: 0° to 50°C; 1% to 90% RH; 0 to 5,000 ppm;
5. Accuracy: ± 0.21°C; ± 2% from 20% to 80% RH; ±50 ppm ±5%;
6. Resolution: 0.024°C at 25°C; 0.01% RH;
7. Size: 7.62 x 12.95 x 4.78 cm;
8. **Cost: € 647.01**

2. HOBO Temperature/Relative Humidity Data Logger – MX1101

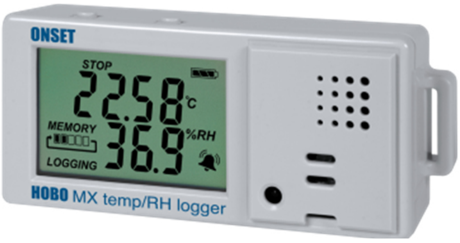


Figure 15. Data logger MX1101
(HOBO Onset, 2022)

Main characteristics of MX1101:

1. Visual and audible high & low alarm thresholds;
2. Mount technology: Wireless;
3. Range: 0° to 50°C; 1% to 90% RH; 0 to 5,000 ppm.
4. Accuracy: ± 0.21°C; ± 2% from 20% to 80% RH; ±50 ppm ±5%;
5. Resolution: 0.024°C at 25°C; 0.01% RH;
6. Size: 7.62 x 12.95 x 4.78 cm;
7. **Cost: € 159.17**

3. HOBO Occupancy/Light (12m Range) Data Logger - UX90-006

Figure 16. Data logger UX90-006
(HOBO Onset, 2015)

Main characteristics of UX90-006:

1. Measures room occupancy up to 12 meters away;
2. Auto-calibration of ON and OFF thresholds ensures reliable readings;
3. Self-calibrating NDIR CO_2 sensor technology ensures optimal accuracy and lower maintenance costs;
4. Communication technology: USB;
5. **Cost: € 277.29**

3.2.3 Alternatives

This section discusses specific sensor alternatives and examples of other solutions that can be considered to implement smart building solutions.

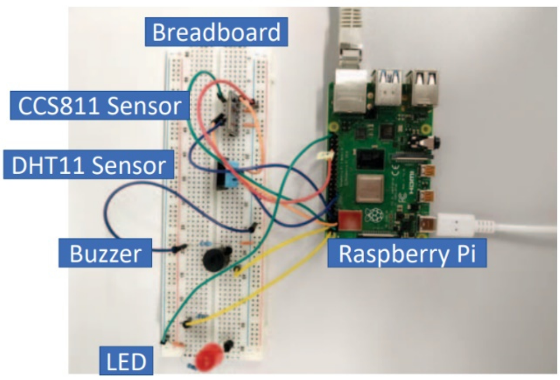


Figure 17. Automation hardware for the air quality use case (Govindasamy et al., 2021)

Low-cost alternatives for smart building sensors include do-it-yourself (DIY) devices, which offer kits and components such as Arduino or Raspberry Pi (shown in Fig. 17). These platforms offer a wide range of sensors (t°, RH, motion, etc.) that can be connected and programmed to meet specific needs. They can work in conjunction with time series databases such as Azure, AWS, Eclipse and OpenHAB, which offer dedicated platforms for creating DTs for further data analysis and graphical representation of sensor data (Govindasamy et al., 2021). These platforms allow the integration of a wide range of sensors and devices, often at a lower cost than proprietary solutions.

Other examples include low-cost wireless sensor networks that use low-power communication protocols such as Zigbee or Z-Wave. These systems often come with a central hub that connects to a smartphone or computer. Brands such as Xiaomi and IKEA offer budget-friendly options.

Figure 18. Xiaomi Automatic Smart Door Lock (Xiaomi, 2021)

For example, Xiaomi offers smart door locks, smart cameras, open/close sensors for windows/doors, etc. A smart door lock, which shown in Fig. 18 offers remote access via the Mi Home app, keyless entry using methods such as PIN codes and fingerprint recognition, access control to manage permissions, security alerts, integration with smart home systems, automatic locking, door status monitoring and logs for activity history.

Other set of alternatives can be implemented through smart plugs and switches, which are an easy way to make existing appliances and devices smarter by enabling remote control through smartphone apps or voice assistants such as Amazon Alexa or Google Home Assistant, energy monitoring by regularly tracking the energy consumption of their appliances and devices, and automation by creating schedules or triggers to automatically turn on and off their appliances and devices based on specific conditions or events (Suryadevara & Biswal, 2019). They can be used to monitor and control power consumption, and are often more budget-friendly than dedicated sensors.

4 DIGITAL TWIN PLANNING

4.1 About the case study building

The building selected for the case study is the home of the Department of Hydrology and Hydraulic Engineering, part of the Faculty of Civil and Geodetic Engineering at the University of Ljubljana, located in Ljubljana, Slovenia. The building is dedicated to teaching, research and professional activities in the following fields: hydrology, erosion and sedimentation, water management, reclamation, hydraulic structures, hydropower, water science, and natural risk management.

Building description: It's a three-storey building with a basement that houses offices for university staff, laboratory and lecture rooms, with a total gross floor area of approximately 3400 square meters (excluding the extension area). The size of the rooms varies according to their purpose. The building has an asymmetrical design with a common area in the center and with two wings - left and right. Offices and classrooms are distributed along central corridors. There are at least two bathrooms on each floor.

Pre-existing status: Before the current study, the building classrooms have been monitored by wall-mounted data loggers, which record measurements of t °, RH and CO_2 for the last 24 hours only, without collecting data, and the building also has an outdoor weather station. However, there is no data on occupancy and lighting patterns, no open-close loggers for windows/blinds and no way to collect data from IAQ sensors.

Figure 19. Hydrology and Hydraulic Engineering Building Hajdrihova 28

4.1.1 Historical review

The building of the Hydrotechnical University is the work of the architect Janez Valentinčič and was built in 1955 for educational purposes (Fig. 20). The building consists of a school part, a high-pressure laboratory and a medium-pressure laboratory. The laboratory, which was built in cooperation with the scientific institutions, trained and still trains personnel for the implementation of hydrotechnical projects and the solution of demanding hydrotechnical problems. In the following, I will refer only to the school section, where the UL FGG premises are located (Zupan, 2015).

The building also belongs to the architectural heritage protected by the Institute for the Protection of Cultural Heritage of Slovenia in Ljubljana (Zupan, 2015).

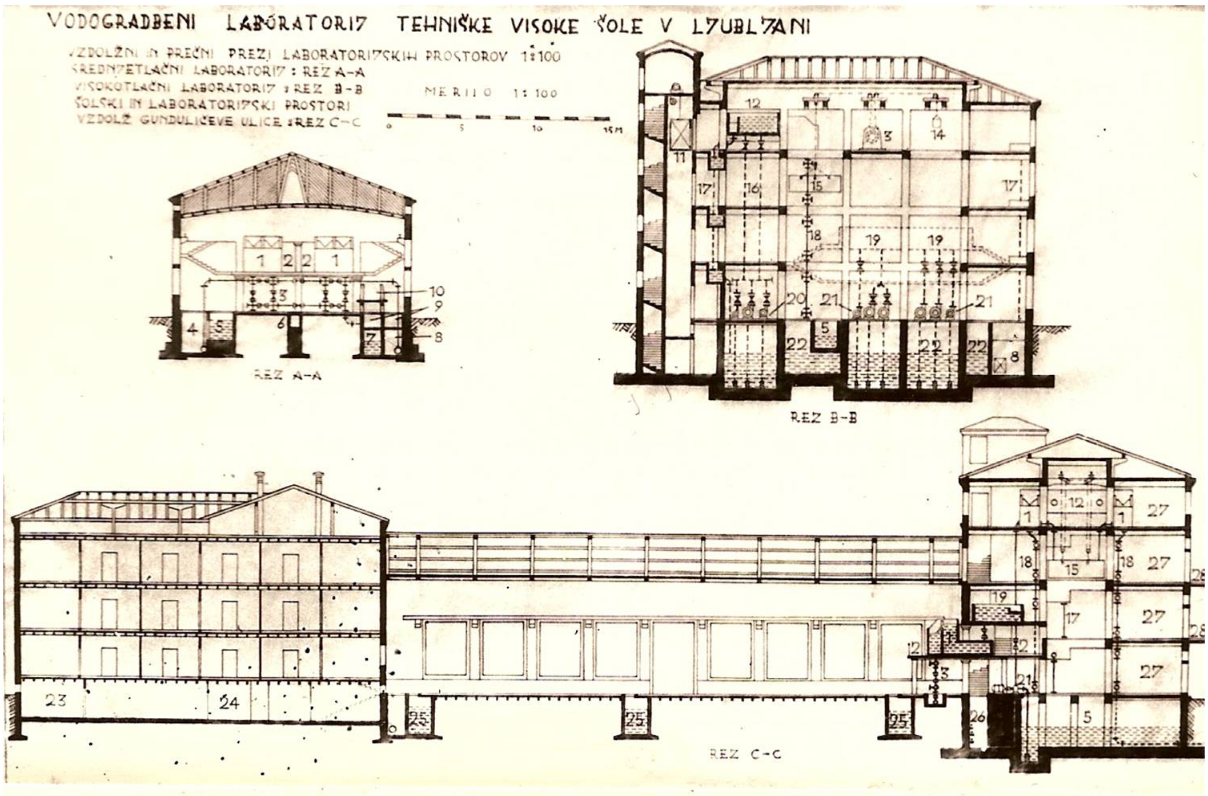


Figure 20. Archived drawing of the building. (Institute for hydraulic research, 2001)

4.1.2 MEP Systems in the build


Figure 21. Flat panel radiator

As for the heating system in the building – the type of radiators is freestanding, flat panel radiators, as shown in Fig. 21, with thermostatic valves and side connections, which are installed in office areas, classrooms and corridors along the external wall under the windows. The system for supplying hot water to the radiators is a two-pipe system with sequential connection of the radiators. The entire pipework is invisible as it runs inside the walls. “Energetika Ljubljana” is responsible for the heat supply. The hot water carrier in the hot water system is chemically treated hot water. The thermal station is installed in the boiler room and has a connected load of 256.93 kW. There is also a gas boiler in the boiler room, which is used to heat the neighboring building of the Hydro Institute (Zupan, 2015).

Electric instant water heaters are used to supply hot water to the toilets and some classes. When the heating of the building was converted to hot water supply, it was decided that the installation of a hot water distribution system in the sanitary facilities was not economically justified. There are 11 electric water heaters in the building with a capacity of 2 kW (Zupan, 2015).

The efficient use of energy for lighting is ensured by using as much natural light as possible, but where this is not possible, energy-efficient lamps and associated elements and appropriate controls must be used. The size of the room and the number of people using it must be taken into account. Tubular fluorescent lighting is installed in classrooms and corridors. The toilets are fitted with low-energy bulbs. The original lighting in the stairwell has been restored. The exterior lighting of the building is equipped with presence sensors that switch off the lights with an adjustable delay when no users are present (Zupan, 2015).


Figure 22. Outdoor AC units

The classrooms are naturally ventilated and cooled, and some offices and laboratories are cooled by electric air conditioners with the outdoor unit installed in the ventilated attic (Fig. 22). The total number of air conditioning units is 12, 2 of which are 5.4 kW and 10 are 3 kW. Lecture room H10 on the ground floor was renovated in 2012 and is ventilated by a ceiling ventilator with a built-in heat recuperator. The maximum cooling capacity of the unit is 14 kW. Heating is also provided by a ventilation unit. The ventilation is electrically controlled and has a detector for the amount of CO_2 in the air, and the blinds are also electrically controlled (Zupan, 2015).

4.1.3 Other important characteristics of the building

Building Envelope: The building envelope serves as the boundary between a structure's interior and the external surroundings. It plays a crucial role in maintaining indoor comfort and quality, regardless of changing outdoor conditions. This envelope comprises numerous elements, including walls, windows (as well as Window-to-Wall Ratio (WWR)), roof, foundation, insulation, thermal mass, and external shading mechanisms, among others (Sadineni et al., 2011). External walls, windows and external shading mechanisms will be reviewed.

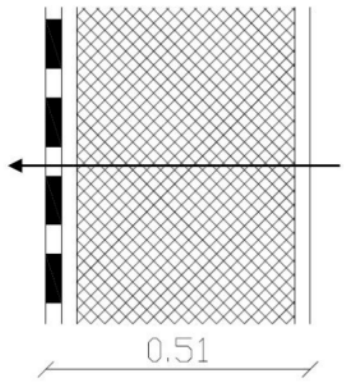


Figure 23. Layers of basement exterior wall

According to Zupan (2015), as for the layers of the external walls – it is slightly different from floor to floor. For the external walls of the basement there are 2 types of such layers, 510 mm and 620 mm thick:

- Lime mortar – 30 mm;
- Reinforced concrete – 420/530mm;
- Extended lime mortar – 30 mm;
- Bitumen – 30 mm.

For ground floor there are again two types of external walls with 490 mm and 620 mm total thickness. Wall composition from inside to outside:

- Expanded lime mortar 30 mm;
- Full-body brick 420/550 mm;
- Expanded lime mortar 30 mm;
- Pigmented façade mortar 10 mm.

And for first and second floor the thickness of the walls has types with 490 and 620 mm thick with composition:

- Extended lime mortar 30 mm;
- Aristos brick 420/550 mm;
- Extended lime mortar 30 mm;
- Pigmented facade mortar 10 mm. (Zupan, 2015).

The original windows were box-shaped with wooden frames. They were replaced in 2005 with new PVC frames, which are less energy efficient. The ground floor entrance doors at the main entrance and at the rear of the building are original wooden doors, partly glazed.

External electrically controlled blinds were installed along with the replacement of the windows. These blinds reduce solar radiation entering the room, consequently lowering the energy needed for summer cooling. (Zupan, 2015).

Potted plants in the building: The presence of potted plants in educational buildings and in classrooms in particular can contribute to a healthier and more comfortable learning environment by reducing air pollutants and improving thermal comfort.

According to a study conducted at the University of Malaya, the placement of potted plants in classrooms resulted in significantly decrease in the level of VOCs, improved thermal comfort, and reduced relative humidity (Jamaludin et al., 2017).

Figure 24. Potted plants in corridors

In addition to improving air quality, the presence of potted plants in classrooms can also have a positive impact on students' perception and satisfaction.

Questionnaire analysis revealed that students spent a significant amount of time in the classroom, and the presence of plants was generally well-received by the students (Jamaludin et al., 2017).

In our case, almost all the potted plants are placed in the corridors, so their efficiency in the main indicators is not as significant as if they were placed in the classrooms, since the students spend most of time there, but it is still quite important for the educational building in general.

4.2 Survey of the building

The DT was based on a model created by students from previous courses. It was modeled in Archicad, saved in IFC format and then loaded into the Dalux Field software in order to be able to check the existing model in the platform, which allows building information to be shared and updated. My role was therefore to check the relevance of the model and comment on what need to be changed in Dalux Field “Forms” tab, and then add missing elements so that it could be used as a basis for further DT implementation.

4.2.1 Model preparation Forms “AS-BUILT Check”

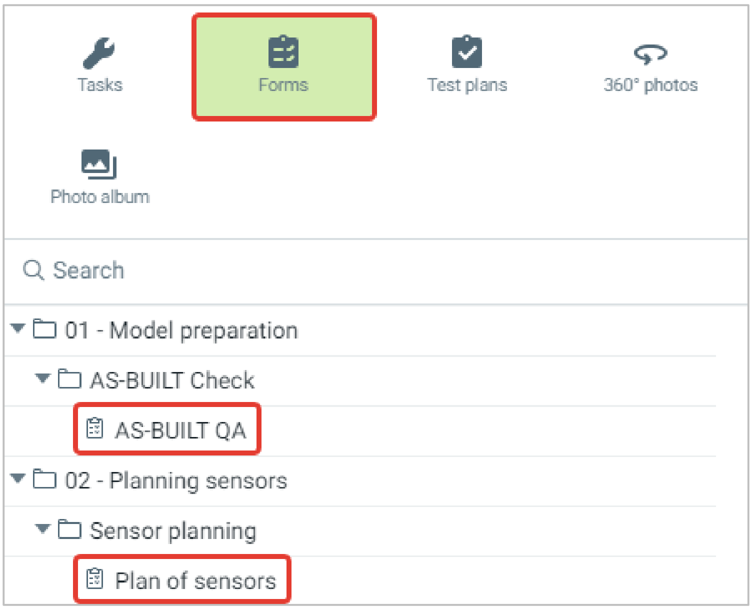


Figure 26. Forms tab in Dalux Field

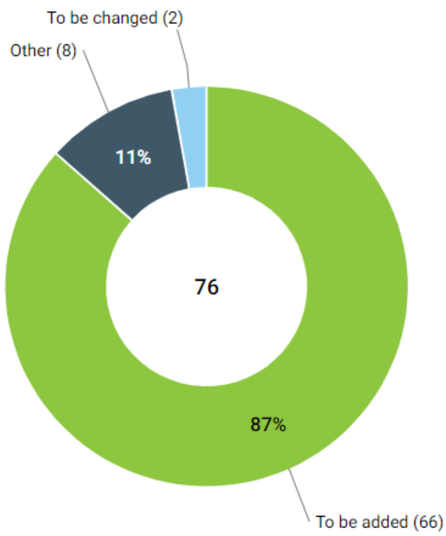


Figure 25. Pie chart showing required actions to be taken

Initially, “Forms” were created according to the model preparation checklist "AS-BUILT QA", where each action to be performed had to be marked as such:

- - To be added;
- - To be removed;
- - To be changed.

As can be seen from the pie chart (Fig. 25) most of what is required is the addition of components to the model.

Accordingly, for each case of discrepancy between the existing model and the real situation, requests for changes in the model were created. The main comments were requests to add furniture, equipment such as AC, radiators, missing plumbing elements and lighting fixtures, as to add missing architectural details to the model.

Each checklist was created for one room and collects information related to that particular room (see Fig. 27). It includes information about the location (level, zone, room name), required actions to be taken, comments about what exact information is missing, visual representation of the exact location on drawings and in the model, photographs to see the comparison between the model and the existing building and details about who created and modified that particular checklist. An example of several checklist forms with comments and attached photos is given in Appx. 1.

BIMQ5 AS-BUILT QA

Project	UL FGG - Inženirski objekti	Created by	Daria Kharchenko
Building	UL FGG - Hajdrihova	Created	May 29 2023, 4:24 PM
Level	Pritličje	Modified by	Daria Kharchenko
3D object category	IfcWall	Modified	Sep 17 2023, 2:27 PM
3D object	Z - 056	Status	Completed
Zone	Common space		

Actions required	To be added
Add furniture, architectural details, inner windows, radiator, lamp, vendor machines	

Changed by Daria Kharchenko, Sep 17 2023, 2:27 PM

Figure 27. AS-BUILT QA checklist in Dalux Field

There are 75 created checklist forms in the project, and as can be seen in Fig. 28 they have a status bar and can be marked as completed.

↑ Memo no.	Modified by	Date modified	Created by	Date created	Stanje	Level	Room
BIMQ3	Daria Kharchenko, UL FGG	May 26 2023, 10:48 PM	Daria Kharchenko, UL FGG	May 24 2023, 6:16 PM	Started		
BIMQ4	Daria Kharchenko, UL FGG	May 29 2023, 4:04 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:01 PM	Started	Pritličje	
BIMQ5	Daria Kharchenko, UL FGG	Sep 17 2023, 2:27 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:24 PM	Completed	Pritličje	
BIMQ6	Daria Kharchenko, UL FGG	Sep 17 2023, 2:27 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:29 PM	Completed	Pritličje	Hodnik
BIMQ7	Daria Kharchenko, UL FGG	May 29 2023, 4:32 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:32 PM	Started	Pritličje	Hodnik
BIMQ8	Daria Kharchenko, UL FGG	Sep 17 2023, 2:27 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:37 PM	Completed	Pritličje	WC
BIMQ9	Daria Kharchenko, UL FGG	May 29 2023, 4:49 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:49 PM	Started	Pritličje	Stopnišce
BIMQ10	Daria Kharchenko, UL FGG	May 29 2023, 4:55 PM	Daria Kharchenko, UL FGG	May 29 2023, 4:55 PM	Started	Nadstropj...	Hodnik
BIMQ11	Daria Kharchenko, UL FGG	May 29 2023, 5:01 PM	Daria Kharchenko, UL FGG	May 29 2023, 5:01 PM	Started	Nadstropj...	Stopnišce
BIMQ12	Daria Kharchenko, UL FGG	May 29 2023, 5:04 PM	Daria Kharchenko, UL FGG	May 29 2023, 5:04 PM	Started	Nadstropj...	WC
BIMQ13	Daria Kharchenko, UL FGG	May 30 2023, 1:44 PM	Daria Kharchenko, UL FGG	May 29 2023, 5:06 PM	Started	Nadstropj...	Predavalni...
BIMQ14	Daria Kharchenko, UL FGG	May 29 2023, 5:11 PM	Daria Kharchenko, UL FGG	May 29 2023, 5:11 PM	Started	Nadstropj...	Hodnik
BIMQ15	Daria Kharchenko, UL FGG	May 29 2023, 5:14 PM	Daria Kharchenko, UL FGG	May 29 2023, 5:14 PM	Started	Nadstropj...	Hodnik 27
BIMQ16	Daria Kharchenko, UL FGG	May 29 2023, 5:17 PM	Daria Kharchenko, UL FGG	May 29 2023, 5:17 PM	Started	Nadstropj...	Računalni...

Figure 28. List of AS-BUILT QA checklists in Dalux Field

The same principle was used to plan the sensors in the “Forms” tab with help of Dalux Field (Fig. 26). More details on the sensor placement strategy are described in subchapter 4.4.

4.2.2 360° photos

Figure 29. RICOH THETA 360° camera

360° photos were also taken for more detailed visualization and information gathering in the simulation.

This was done using the RICOH THETA X 360° camera, which can be attached to a construction helmet to control the capture of such photos in relation to the camera's position in space. This camera works directly with Dalux Field, so no additional applications were needed to upload photos there.

Once the camera was connected to the Dalux Field application, taking a photo involved selecting a point on the floor plan within Dalux Field, standing in that location, and initiating the photo capture. Within 5-10 seconds, the camera would signal when the image was ready, and it would be automatically uploaded to Dalux Field.

For example, Fig. 30 shows that the model does not have the furniture, radiators, and lighting in place for the classroom "Predavalnica 40". Otherwise, the model corresponds to reality - the windows are at the correct height, the classroom is slightly sloping.

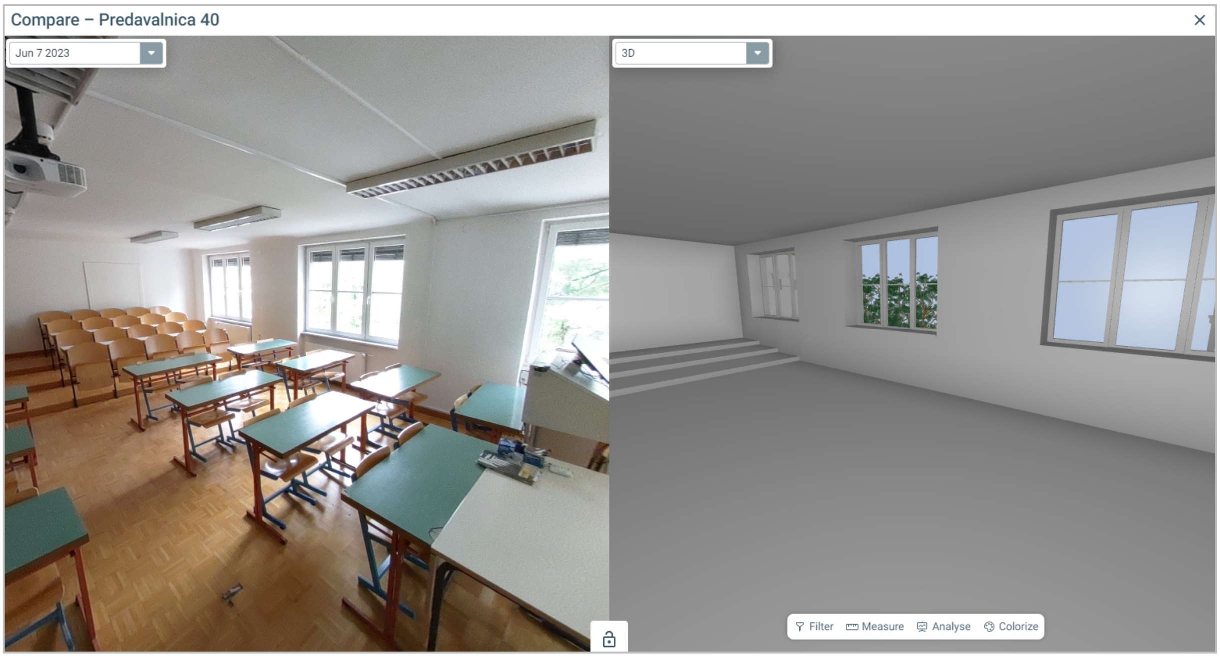


Figure 30. Comparison between 360° photos and model for the classroom 40

And in Fig. 31 it can be seen that in the library room “Knjiznica 29” the size of the windows is incorrect and furniture, radiators and lighting are missing.

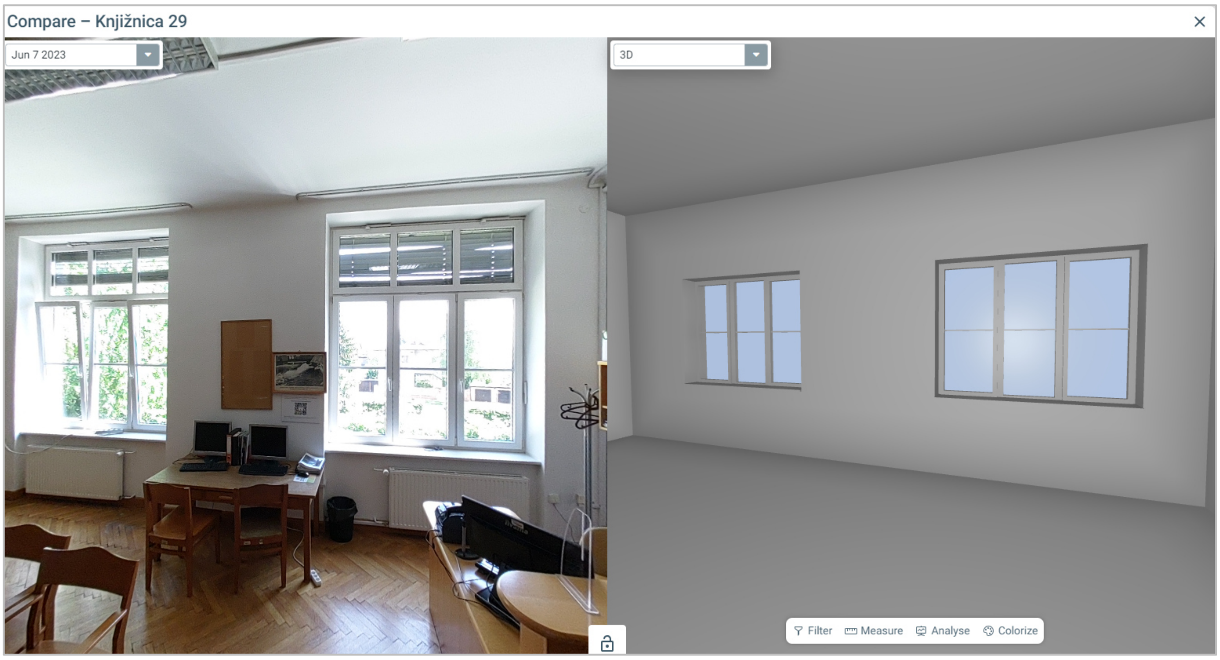


Figure 31. Comparison between 360° photos and model for the library room

In this way, the 360° photos serve as an excellent supplement to the comparison between the model and the existing building.

4.3 BIM Execution Plan

In this case, we are developing a BIM Execution Plan (BEP) to update the existing model, with a specific focus on modeling preparation.

As the existing model of the building was coarsely detailed and didn't take into account the placement of important building components such as educational, laboratory and office furniture and equipment, plumbing fixtures, HVAC equipment etc., it was decided to update the model. To this end, an IFC file containing the geometry from Archicad was taken as a substrate for further development in Revit software. A BEP was therefore created to plan the necessary modelling work. The key information regarding the purpose of the modelling update is highlighted below.

This BEP was created using Plannerly – the BIM management platform for creating this type of document with a large number of provided templates depending on the project standard used. In this case the LOD US BIM Forum standard was used.

4.3.1 Project BIM Uses

As for BIM (Model) Uses for the project, a list of it was chosen from Domain Model Uses, Uses which are *"applicable to a specific Industry, its relevant knowledge domain and information systems."* (Succar, 2019). The main BIM Uses with their codes and descriptions that are relevant to the DT creation and analysis project are listed in Tab. 2.

Table 2. Project BIM Uses.

Code	BIM Use	Description from BIM Dictionary (2019)	Priority*
2020	3D detailing	*"A Model Use, representing how three-dimensional details are extracted from information-rich 3D models. 3D Detailing typically includes hybrid 2D-3D annotated views".*	High
2030	As-constructed Representation	*"A Model Use where 3D models are generated to serve as temporary As-Built Models or more permanent Record Models. As-constructed Representation are based on either manual means (e.g. using a tape measure) and/or semi-automated processes".*	High
2070	Record Keeping	*"A Model Use representing how 3D models are generated and maintained as Record Models, where a Record Model is an accurate representation of an existing Facility; its spaces, assets, physical condition and surrounding environment. The Record Model may link to other records (documents, drawings, images, etc.) and include equipment manufacturer data, maintenance schedules, warranties and space conditions/damages".*	High
4090	Energy Utilization	*"A Model Use and a Building Performance metric measuring how and how-much a Facility consumes energy. High-performance buildings typically consume less energy (electricity for lighting, fossil fuels for heating, etc.) than other comparable buildings".*	High
6010	Asset Maintenance	*"A Model Use where 3D models are used to manage the maintenance of Assets by linking objects to external databases through specialized middleware. Asset Maintenance is a subset of Asset Management".*	Medium
7030	Performance Monitoring	*"A Model Use representing how 3D models are used to monitor and manage Energy Utilization and other Building Performance metrics".*	High
7040	Real-time Utilization	*"Model Use, representing how 3D models are used to display information fed in real-time from sensors distributed around a building or site. Information may include current occupancy, temperature, humidity, toxicity and energy consumption".*	High
8050	BIM/IoT Interfacing	*"A Model Use representing how BIM models are used as an interface for the IoT, a network of equipment, sensors, wearables, and benefit from the data feeds for Building Automation, Real-time Utilization and Asset Tracking"*	High

Each BIM Use is closely linked to the DT scenarios in our case study:

- **3D detailing** is essential for analyzing the position of elements in space;
- **As-constructed** Representation and keeping the model in the actual representation with all the data on the reconstruction and/or retrofitting carried out allows the DT to be maintained in the as-built state;
- **Record Keeping** allows to manage all types of engineering data, because once it loaded into a database, we can use it in a variety of ways;
- **Energy Utilization** allows to analyze how to optimize energy consumption;
- **Asset Maintenance** allows to optimize utilization of items, things or entities *“that have potential or actual value to an organization”* (BIM Dictionary, 2019).
- **Performance Monitoring** allows to analyze how to optimize any type of resource consumption;
- **Real-time Utilization** can be useful for further regulation of building characteristics using real-time data collected from data loggers or sensors;
- **BIM/IoT Interfacing** is a fundamental aspect of working with DT.

4.3.2 Project Coordinates

Identify the spatial location of the project according to the master plan; real world coordinates, level system and project rotation have been set in Base Point. All required coordination characteristics are recorded in Tab. 3.

Table 3. Project coordinates

Physical Project Coordinates:		
Site name	UL_FGG	
Base Point	0,0,0	
Height Datum	291.8	
Project Location	N/S: 5055468.6	E/W: 476723.6
Project Rotation / Positioning	Degrees: 244°	

4.3.3 Software versions

The main software used is presented in Tab. 4:

Table 4. Software versions.

Discipline	BIM Use	Software	Version	Icon
Making a building survey	Record Keeping	Dalux Field	Always Current	
Sensors placement strategy	Real-time Utilization	Dalux Field	Always Current	
Detailed Architectural Model	3D detailing	AutoDesk Revit	2022	
DT Prototype	BIM/IoT Interfacing	AutoDesk Tandem	Always Current	

4.3.4 Level of Detail

Development is based on the BIM Forum Level of Development (LOD) Specification which covers the geometry and information representation of the project. Elements from the AS-IS column (Appx. 2 and Tab. 5 as an example) have been mainly developed at LOD 200 (*"The Model Element is graphically represented within the Model as a generic system, object, or assembly with quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element."* (BIMForum, 2020)), while for the TO-BE model, these elements should be developed at LOD 300 (*"The Model Element is graphically represented within the Model as a system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element."* (BIMForum, 2020)), Fig. 32 illustrates the different type of LOD representation for Exterior Masonry Wall.

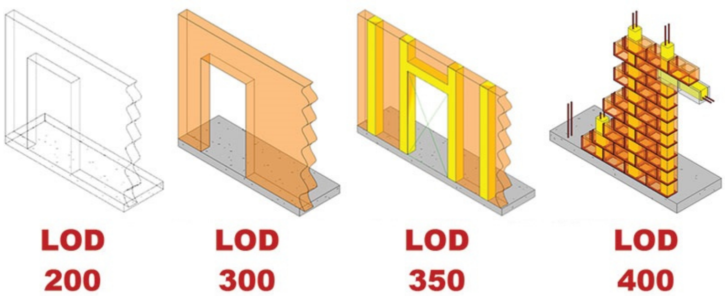


Figure 32. A masonry wall element LOD progression. (BIMForum, 2020)

AS-IS model was obtained in IFC format and was made in Archicad. As seen in (Fig. 33: left image), it lacked detail and was unsuitable for DT implementation purposes. Consequently, a more detailed model was developed, as illustrated in (Fig. 33: right image).

The Level of Detail table (Appx. 2 and Tab. 5 as a shortened example), shows the model's progression through two milestones: AS-IS and TO-BE. In the AS-IS stage, the table indicates how the model was initially created, and all empty table cells mean that elements weren't elaborated at that milestone. Conversely, the TO-BE column represents LOD required to support all scenarios considered for the DT implementation.

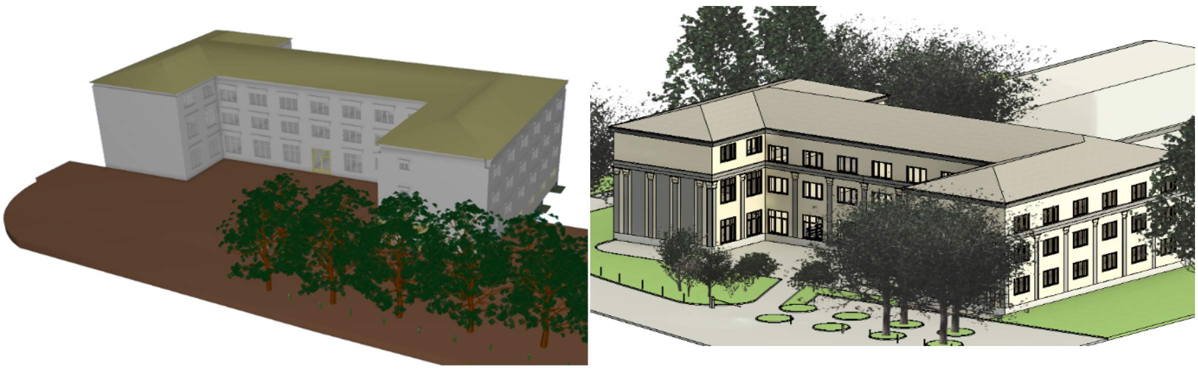
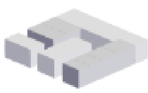
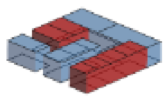
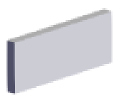
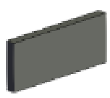
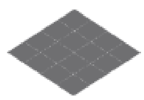
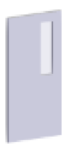
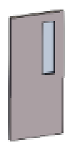
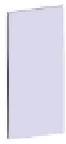


Figure 33. Representation of the AS-IS and TO-BE models

The full Level of Detail table can be found in Appx. 2.

Table 5. Example of LOD table.

	AS-IS		TO-BE	
Project setup				
1. Architecture				
Rooms	200		300	
Partition Walls	200		300	
Ceilings	200		300	
Interior Doors	200		300	

Exterior Doors	200		300	
Windows	200		300	

4.4 Sensors placement strategy

The main aim of placing data loggers/sensors is the ability to collect, analyze and optimize data from it, where:

- Indoor climate must be adopted to the well-being of end-users who are studying and working at the building;
- The building of campus must save energy by reducing over-usage of energy to minimum.

It is crucial to place sensors where it would be possible to receive the most accurate and relevant readings and to have an ability to maintain satisfactory control by the Building Automation Systems (BAS) if needed. That is why sensors should be placed by certain rules.

Rules of placement and mounting sensors can be different depending on functional type of sensor. And also some of them are sold as an assemble of several sensors (e.g. Air quality sensors)., that is why it is simpler to group sensors by their functioning and implement set of rules how to place it in accordance of their type.

4.4.1 Rules of placement IAQ sensors (t°, RH, CO_2, etc.):

1. **Height Placement:** Install sensors at a height above the finished floor of approximately 1.2 - 1.8 meters, closer to where occupants work. This height aligns with the average person's breathing zone, ensuring that measurements closely represent end-users' perceptions.
2. **Distance from Walls:** Position sensors at least 50 cm away from the nearest wall. Avoid placing them on shelves or in alcoves, as these locations can disrupt airflow and lead to inaccurate readings.
3. **Avoidance of Environmental Factors:** Prevent exposure to direct sunlight, proximity to windows, ventilation units, excessive air movement, heat sources, or areas covered with curtains or obstructions. These factors can interfere with accurate detection.

4. **Check Wall Obstructions:** Ensure there are no pipes or obstructions within the wall behind the sensor, as this can affect air circulation and measurements.
5. **Avoid External Walls:** Do not place sensors on external wall surfaces, as air penetration through these walls can lead to inaccurate readings due to outdoor influences.
6. **Room Dedication:** Ideally, dedicate an air quality sensor for each room to monitor specific air characteristics accurately. If sharing a sensor between two rooms is necessary, ensure these rooms have similar conditions regarding exterior and interior walls, orientation (e.g., north-facing), and heating/cooling requirements to maintain measurement reliability.

Figure 34. Placement of IAQ Sensors in the Basement

Memo no.	Senzor type	↑ Level	Room	Created by
SP4	Rh, T	Klet		Daria Kharchenko, UL FGG
SP5	CO2, Rh, T	Klet		Daria Kharchenko, UL FGG
SP6	Rh, T	Klet	KMTe 11	Daria Kharchenko, UL FGG
SP7	Rh, T	Klet		Daria Kharchenko, UL FGG

Figure 35. List of IAQ Sensors in the Basement

Regarding the Basement floor it primarily serves as a technical area with storage for books and equipment, as well as housing laboratories and one classroom. Therefore, it becomes essential to monitor the t°, RH in the library and laboratories to preserve the integrity of the books and equipment, shielding them from excessive humidity levels. Additionally, since occupants usually spend extended periods in the classroom, it is essential to monitor air factors like t°, RH, CO_2 there to ensure a comfortable and safe environment (as it seen in Fig. 35).

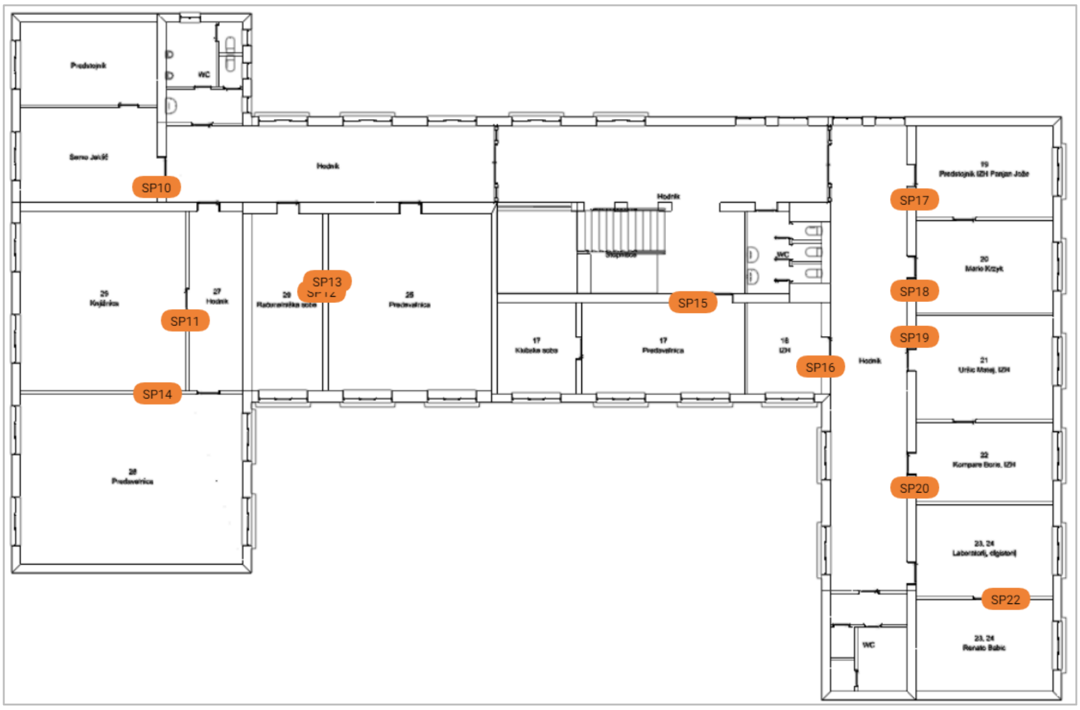


Figure 36. Placement of IAQ Sensors in the First Floor

Memo no.	Senzor type	↑ Level	Room	Created by
SP10	Rh, T	Nadstropje 1	Samo Jaklič	Daria Kharchenko, UL FGG
SP11	CO2, Rh, T	Nadstropje 1	Knjižnica 29	Daria Kharchenko, UL FGG
SP12	CO2, Rh, T	Nadstropje 1		Daria Kharchenko, UL FGG
SP13	CO2, Rh, T	Nadstropje 1	Predavalnica ...	Daria Kharchenko, UL FGG
SP14	CO2, Rh, T	Nadstropje 1		Daria Kharchenko, UL FGG
SP15	Rh, T	Nadstropje 1	Predavalnica ...	Daria Kharchenko, UL FGG
SP16	Rh, T	Nadstropje 1	IZH 16	Daria Kharchenko, UL FGG
SP17	Rh, T	Nadstropje 1	Predstojnik IZ...	Daria Kharchenko, UL FGG
SP18	Rh, T	Nadstropje 1	Mario Krzyk 20	Daria Kharchenko, UL FGG
SP19	Rh, T	Nadstropje 1	Uršic Matej, I...	Daria Kharchenko, UL FGG
SP20	Rh, T	Nadstropje 1	Kompare Bori...	Daria Kharchenko, UL FGG
SP22	CO2, Rh, T	Nadstropje 1		Daria Kharchenko, UL FGG

Figure 37. List of IAQ Sensors in the First Floor

Using the first floor as an example of how IAQ sensors should be positioned on other floors (Ground floor and Second floor), as it represents a typical layout with similar space utilization principles, it's evident that occupants spend a significant amount of time in classrooms throughout the day. Therefore, it becomes essential to closely monitor key factors such as t°, RH, and CO_2 levels, as these elements have a profound impact on the overall well-being of the occupants. Additionally, measuring these characteristics in laboratories is also important. In all other spaces, such as offices, only t° and RH will be measured.

4.4.2 Rules of placement occupancy and light data loggers:

1. **Deployment:** It can vary depending on the manufacturer and type of sensor. For example, "HOBO Occupancy/Light Data Logger - UX90-006" sensor to be used covers 12 m.
2. **Height Placement:** Install the sensor at a height of approximately 1.2 - 1.8 meters above the finished floor, positioned in areas where occupants typically move and work. This height is suitable for detecting both occupancy and light levels accurately.
3. **Coverage Area:** Place the combined sensor strategically within the room to ensure optimal coverage for both occupancy detection and light measurement. Consider the room layout, furniture placement, and expected paths of occupants to achieve even coverage.

4. **Away from Obstructions:** Ensure that the sensor's view is not obstructed by furniture, shelves, or objects that can block its line of sight for both occupancy and light measurements.
5. **Avoid Direct Sunlight:** Position the sensor away from direct sunlight exposure to prevent false readings caused by temporary changes in light levels due to sunlight. This is particularly important for accurate light level measurements.
6. **Proximity to Light Sources:** When measuring light levels in specific areas, place the sensor near relevant light fixtures, work surfaces, or sources of interest to capture precise lighting conditions.
7. **Sensitivity Adjustment:** Configure the sensor's sensitivity settings to match the desired functionality. For example, adjust occupancy sensitivity to detect occupants' movements effectively, and configure the light sensor to respond appropriately to changes in ambient lighting.
8. **Regular Maintenance:** Periodically inspect and clean the sensor to ensure it remains free of dust or obstructions that could affect its accuracy over time.

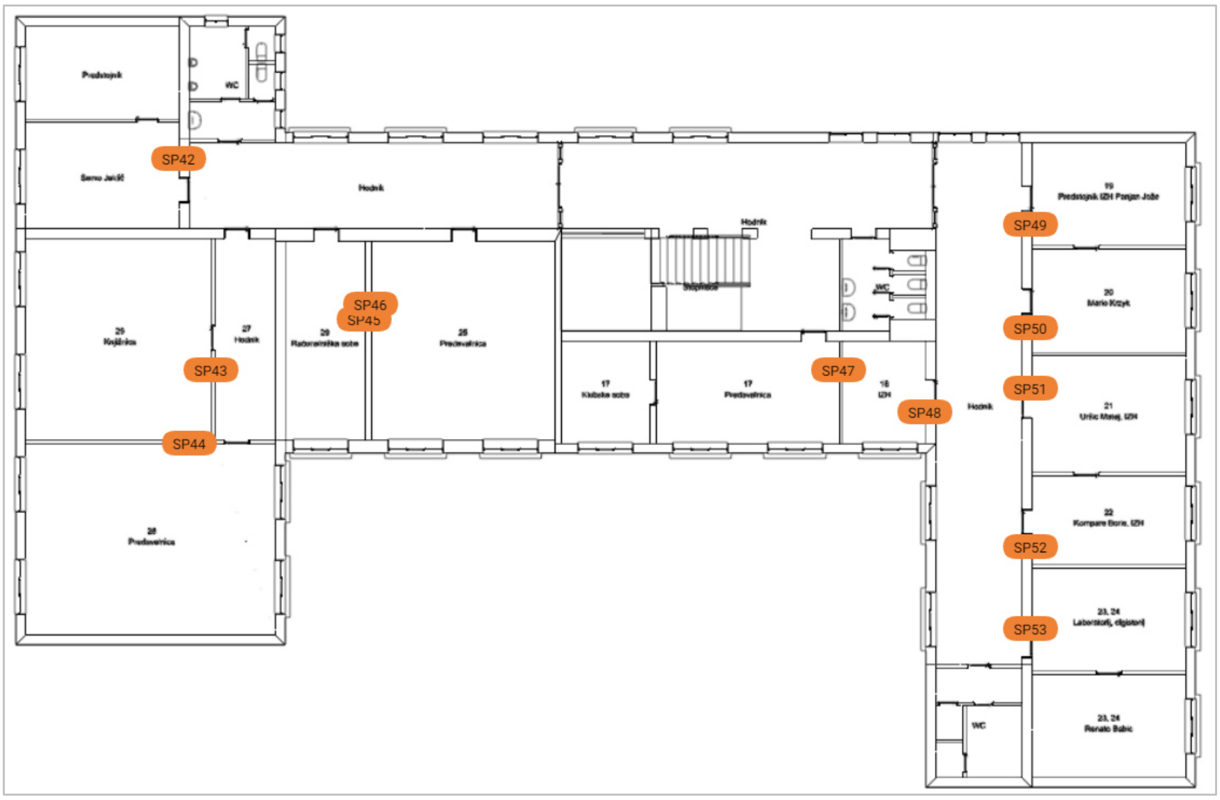


Figure 38. Placement of Occupancy/Light Sensors in the First Floor

Memo no.	Senzor type	Level	Room	Created by
SP42	Lu, Presence indicator	Nadstropje 1	Samo Jaklič	Daria Kharchenko, UL FGG
SP43	Lu, Presence indicator	Nadstropje 1	Knjižnica 29	Daria Kharchenko, UL FGG
SP44	Lu, Presence indicator	Nadstropje 1		Daria Kharchenko, UL FGG
SP45	Lu, Presence indicator	Nadstropje 1		Daria Kharchenko, UL FGG
SP46	Lu, Presence indicator	Nadstropje 1	Predavalnica ...	Daria Kharchenko, UL FGG
SP47	Lu, Presence indicator	Nadstropje 1	Predavalnica ...	Daria Kharchenko, UL FGG
SP48	Lu, Presence indicator	Nadstropje 1	IZH 16	Daria Kharchenko, UL FGG
SP49	Lu, Presence indicator	Nadstropje 1	Predstojnik IZ...	Daria Kharchenko, UL FGG
SP50	Lu, Presence indicator	Nadstropje 1	Mario Krzyk 20	Daria Kharchenko, UL FGG
SP51	Lu, Presence indicator	Nadstropje 1	Uršic Matej, I...	Daria Kharchenko, UL FGG
SP52	Lu, Presence indicator	Nadstropje 1	Kompare Bori...	Daria Kharchenko, UL FGG
SP53	Lu, Presence indicator	Nadstropje 1	Laboratorij, di...	Daria Kharchenko, UL FGG

Figure 39. List of Occupancy/Light Sensors in the First Floor

A combined occupancy and light sensor offers the advantage of optimizing both energy efficiency and user comfort by adjusting lighting levels according to occupancy. Proper placement ensures that both functions work seamlessly, contributing to energy savings and a comfortable indoor environment. The example of the first floor in Fig. 38 and 39 shows the principle of sensor placement (the principle is the same for the other floors): sensors are placed in rooms where students, teachers and other workers spend the most of their time - classrooms, offices and laboratories.

4.4.3 Rules of placement other data loggers/sensors

- **Flood /leak sensor placement:** In the context of water damage mitigation, the judicious placement of flood or leak sensors is critical. These sensors should be strategically placed in key locations such as the lowest areas, near potential water sources such as appliances and plumbing, under sinks and around larger spaces. It is advisable to position these sensors slightly above floor level, to ensure accessibility for routine testing and maintenance, with due attention to regular battery replacement.
- **Rules of placement open/close loggers:** For accurate and efficient operation of open/close loggers for windows and blinds, place window loggers near the window frame, securely attached at a consistent height, away from obstructions, direct sunlight, and extreme temperatures. For blind loggers, position them near the blind mechanism

with a clear line of sight, securely mounted, and at a uniform distance and height from the blinds.

- **Rules of placement smart meters:** Strategically positioning smart water meters close to the primary water supply entry point ensures accurate measurement of water inflow. Priority should be given to accessibility and a well-lit environment for ease of maintenance, while protecting against obstructions and extreme temperatures. Similarly, smart energy meters should be installed close to the electrical panel for accurate monitoring of electricity consumption, taking into account accessibility, wiring and weatherproof enclosures when installed outdoors.
- **Rules of placement smart thermostats:** Optimal placement of smart thermostats is essential for efficient climate control. Central positioning on interior walls improves temperature monitoring and control. Avoiding draughts, vents, radiators or direct sunlight prevents temperature inaccuracies. Mounting thermostats at eye level improves accessibility and readability, while avoiding proximity to heat sources maintains accuracy, and ensuring strong Wi-Fi signals is critical for remote control.

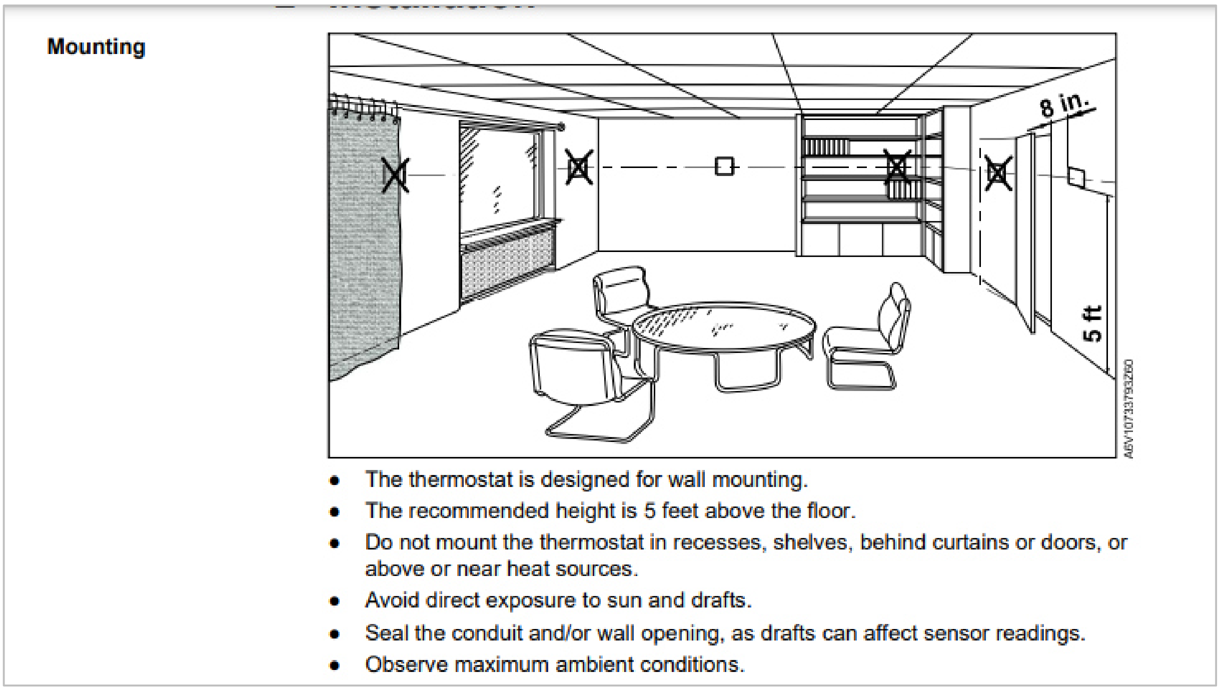


Figure 40. Example of mounting requirements for Smart Thermostat (Siemens, 2021).

4.5 Approximate economic calculation [1]

Since the Onset HOBO solution was chosen, the entire selection of sensors and components is based on the pricing information from their official website.
As for t°, RH, CO_2 sensor type – **HOBO MX1102A Data Logger** was chosen;
For t°, RH sensor type – **HOBO MX1101 Data Logger** was chosen;
And for Occupancy +Light sensor type – **HOBO UX90-006 Data Logger.**

Table 6. Sensor installation cost estimation.

Type of Sensor	Basement	Ground Floor	First Floor	Second Floor	Total ammount	Cost per piece, €	Total cost, €
t°, RH, CO_2	1	2	6	1	10	650.16	6501.6
t°, RH	3	-	7	13	20	159.96	3199.2
Occ. + Light	3	3	12	18	36	277.29	9982.44
Gateway	-	-	1	-	1	387	387
							20070.24

Also taking into account that we made planning for a DT, the price of an annual subscription to the software for working with DTs should be taken into account. From the previously proposed solutions more suitable is Autodesk Tandem. Accordingly, to their official website their subscription will cost **3,150 USD**/Year including 10,000 assets, 2,000 streams and 3 years of time-series history.

[1] All the prices are current as of September 2023.

5 DIGITAL TWIN PROTOTYPING

At this stage, the following DT scenario is considered: Real-time monitoring of environmental conditions. For this purpose, Autodesk Tandem was used in a 14-day demo version. So, prepared model was uploaded to that web-platform Autodesk Tandem (Fig. 41).

Figure 41.Preview of facility in Autodesk Tandem

5.1 Data from the model

Firstly, it is essential to update the assets, i.e. those elements that directly affect the performance of the building. This includes an assessment of MEP system equipment and envelope components to ensure accurate data completion. When considering specific scenarios for DT analysis, it becomes clear that it is critical to verify and supplement data for both envelope components and equipment. This is essential to include their energy consumption metrics and, in the case of envelope elements, their thermal characteristics such as thermal conductivity, which is directly influenced by the construction material used. The data required to update the equipment and envelope characteristics are given in Section 4.1. For the prepared model, assets include external walls, windows, doors, roof, foundations, as well as equipment such as radiators, air conditioning, lighting fixtures, plumbing fixtures and related components.

5.2 Stream placement and adjustment

Streams are the data points or measurements, such as temperature and vibration, that result from the connection of a physical device or sensor within Autodesk Tandem (Fig. 42). These data points are captured at a user-defined frequency and then archived for a specified retention period, creating a time series history.

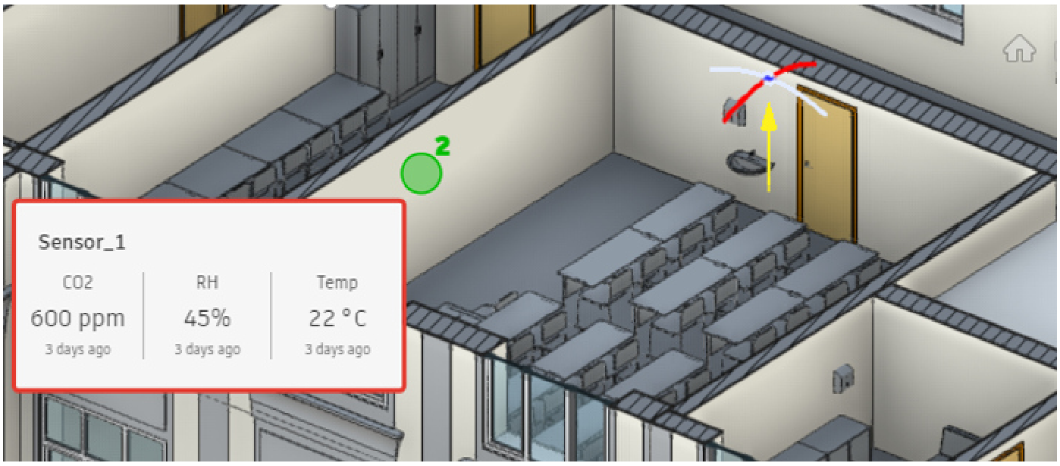


Figure 42. Data from a particular Stream

Before creating a stream, it is necessary to create a facility (a project) and assign a facility template containing a classification and the required parameters to map to data from sensors. For example, for this project parameters such as t °, RH, CO_2 need to be monitored.

To continue, the streams on the first floor of the DT prototype were placed, following the sensor placement strategy described in detail in Subchapter 4.4.1. This sensor's placement serves to visually demonstrate the collection of sensor data and the subsequent generation of heat maps.

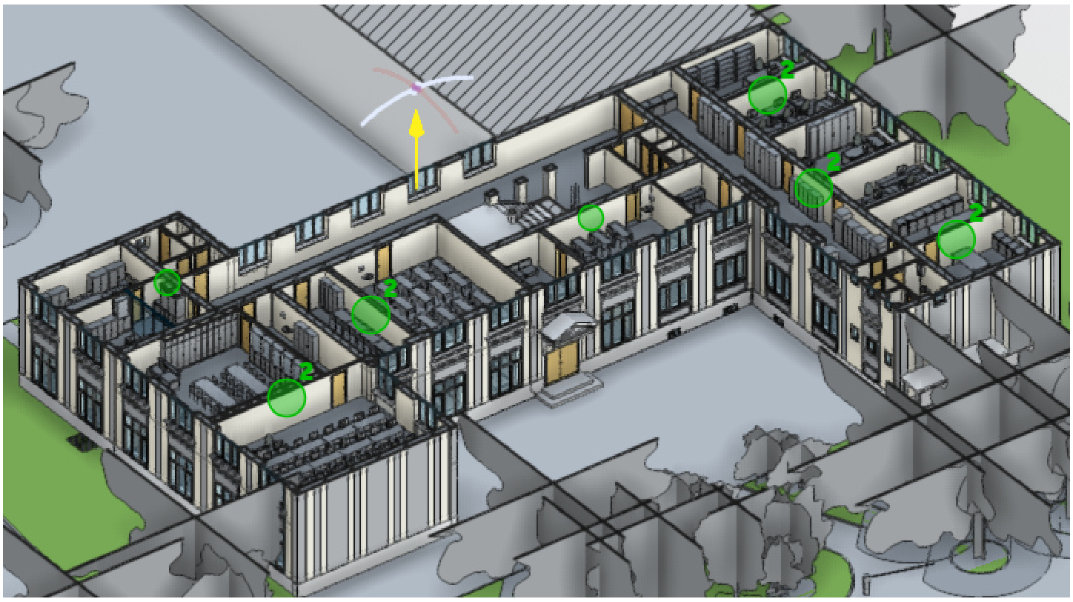


Figure 43. Placed Streams in the First Floor

5.3 Time-series data from various sensors

Since there is no actual data from the sensors at this stage, they were recreated by sending randomized information with data in JSON format through the Postman application. Main requirements to devices from Autodesk Tandem are:

1. First, the device needs to be able to return data in a simple JSON format using key-value pairs*. Below is an example:

   "Date": "2023-03-21T01:15:00Z"

   "Tempurature (C)": 41

2. And the device or service needs to be able to POST to an HTTP endpoint.

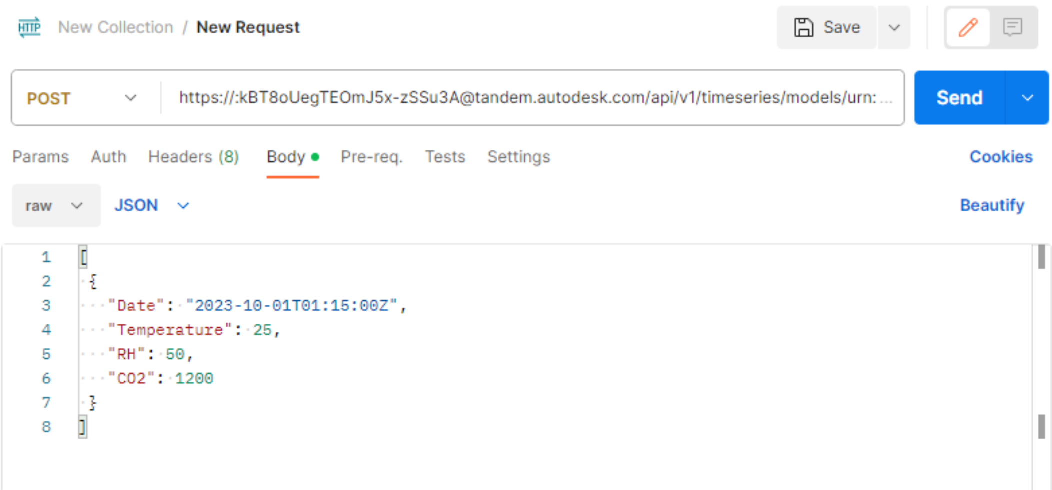


Figure 44. Data generation and transmission to Streams from Postman App

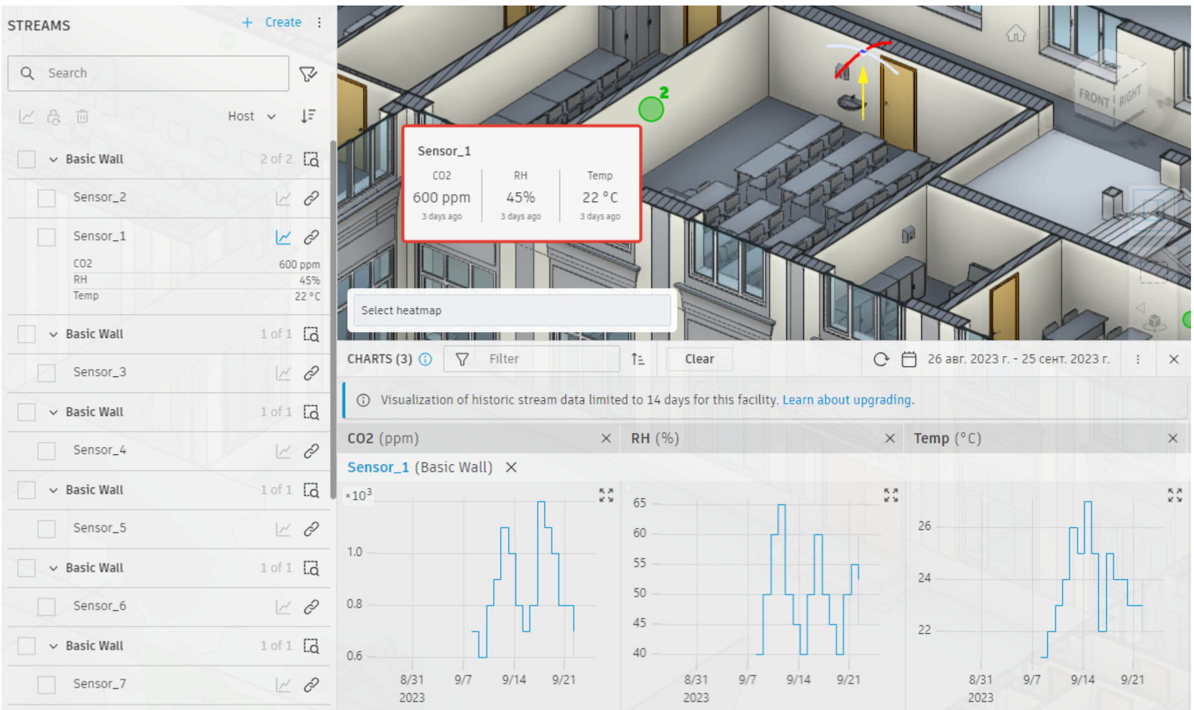


Figure 45. Generated data in chart view from Sensor 1

5.4 Sensor Data Visualization

Once the necessary information had been collected, heat maps of real time t °, RH, CO_2 levels was generated to provide a visual understanding of the building's performance.

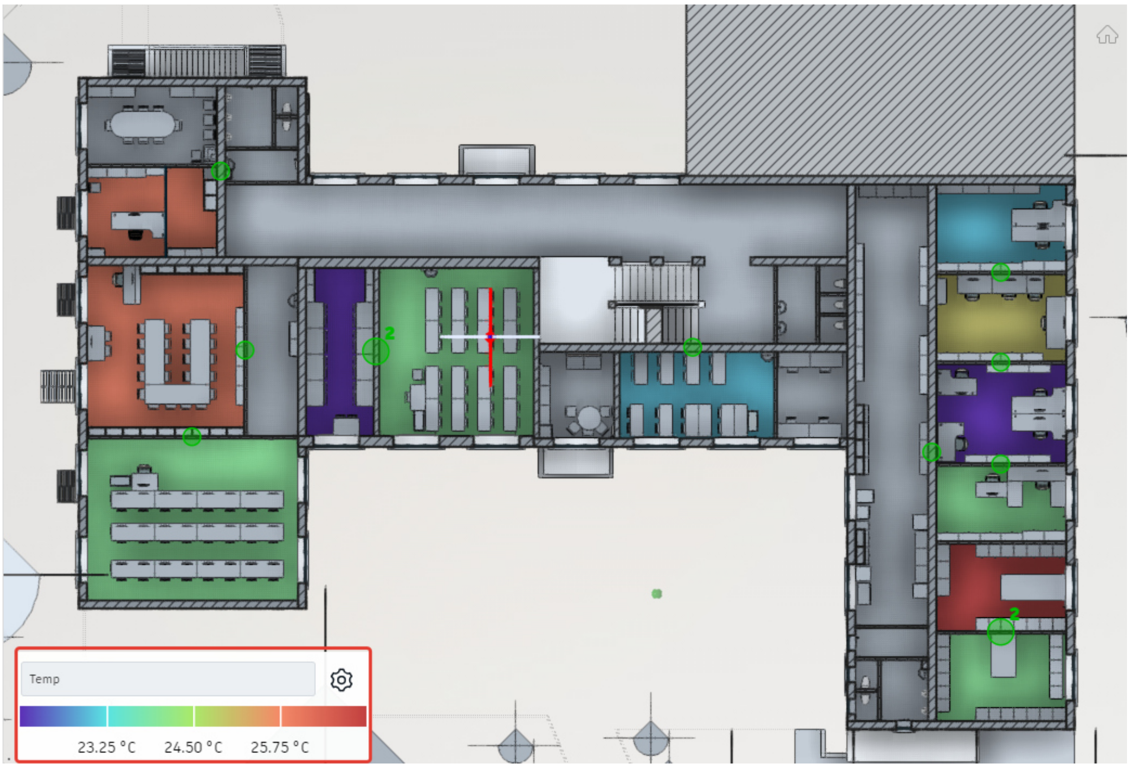


Figure 46. Heat map of real time t °

Figure 47. Heat map of real time RH

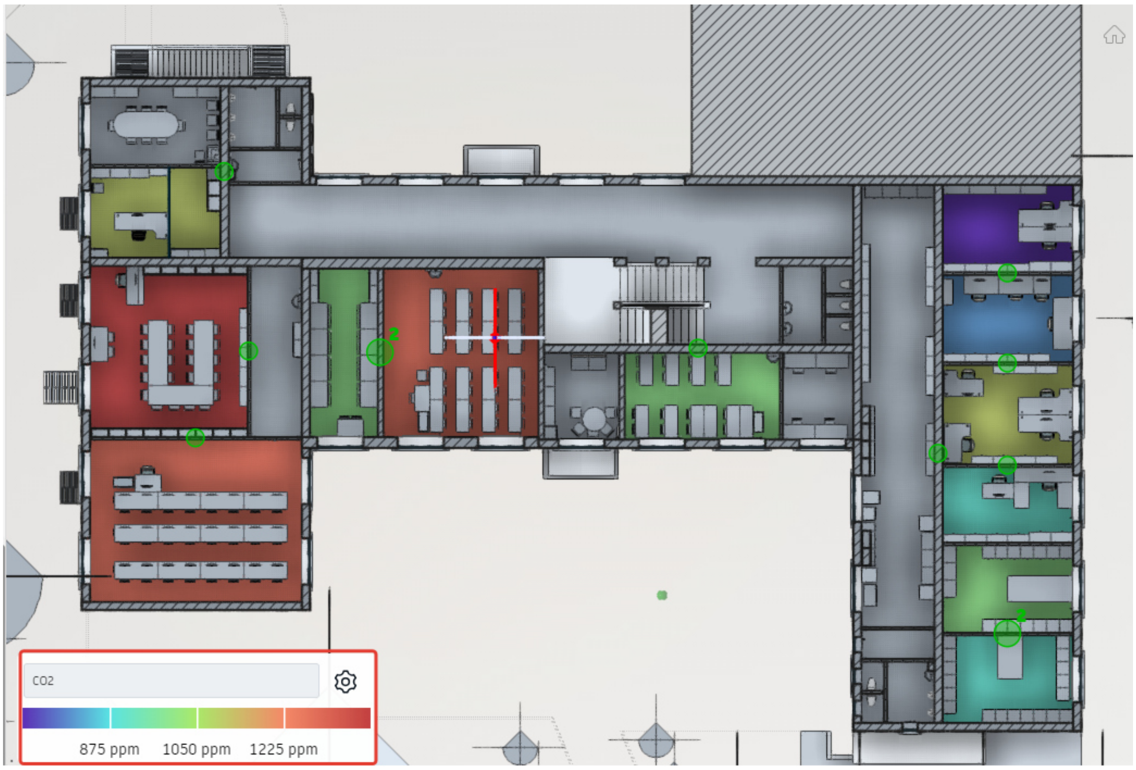


Figure 48. Heat map of real time CO_2 levels

Each color of the room implies a different range of parameter values from minimum (blue) to maximum (red).

5.5 Benefits of using Autodesk Tandem

In summary, Autodesk Tandem is proving to be a powerful and versatile tool for working with DT data. Its intuitive and visually appealing web-based interface provides a user-friendly experience. Furthermore, the application's capabilities go beyond shown features, allowing users to customize access permissions, link relevant certificates or installation documentation, and benefit from the convenience of browser-based access, eliminating the need for software downloads and computer compatibility concerns. This comprehensive approach enables flexible and efficient management of engineering data.

6 DISCUSSION

6.1 Case study analysis

In this section, the analysis focuses on the case study, which is divided into two milestones: " Digital Twin Planning" and "Digital Twin Prototyping". These milestones provided an opportunity to explore the feasibility of implementing DT for particular educational building.

During the planning phase, the sensor placement strategy was significantly influenced by the choice of a specific sensor manufacturer, HOBO Onset. This strategic decision had an impact on the final sensor placement and cost estimates. Choosing a different manufacturer would likely have resulted in different sensor layouts and associated costs. The choice of HOBO Onset was based on a number of factors, including cost effectiveness and ease of deployment.

The successful implementation of Milestone 2 depended directly on the choice of software. Autodesk Tandem played a key role in shaping the final outcome of the DT project. The main advantage of the software is its web-based platform, which not only increases operational flexibility, but also eliminates the need to address hardware-related concerns. In addition, the software's ability to accommodate multiple participants with customizable access rights ensures efficient data management and collaboration, facilitating effective regulation of data access.

6.2 Challenges and limitations of the process

DT Level of Maturity: The implementation of DT poses such challenges as requiring a high level of Digital Built Environment maturity from asset management organizations responsible for engineering data. These challenges become apparent when assessing three critical areas: Digital Capability (which includes Data Management, Data Analysis and Decision Making), Organizational Environment (which includes People, Processes and Technology infrastructure within the organization) and the different stages of Digital Twin Maturity, including Ad-hoc Datasets, Digital Twin Formation, Digital Twin Standard Operation, Digital Twin Real-Time Automation and Digital Twin Intelligence Contextualization (Papic & Cerovsek, 2019).

In order to identify areas for improvement, it is advisable to assess the digital capability level of asset management in the context of the Hydrology and Hydraulic Engineering Building at Hajdrihova 28.

Financial constraints: The implementation of the DT solution was initially planned within tight budgetary constraints. Decisions regarding both software and hardware were heavily influenced by financial considerations, necessitating a focus on cost-effectiveness throughout the project.

Sensor Limitations: A particular interest from the project supervisors in a specific sensor manufacturer imposed restrictions on the sensor placement strategy. t°, RH, CO_2 levels, occupancy patterns and light monitoring were considered, but sensors such as smart thermostats, window/blind open/close data loggers and leak detection sensors weren't considered due to limitations within the manufacturer's product range.

Integration complexity: Integrating sensors with Smart Building Cloud Platforms and specialized software for DTs presented some complexities. These complexities extended to the analysis of communication protocols, the ability to store historical sensor data, and the difficulties in implementing specific DT scenarios.

Data access restrictions: Some software and hardware vendors did not make pricing information readily available, and in some cases imposed specific conditions on access to the data. This lack of transparency and flexibility was a challenge in the context of a research project where purchases could not be guaranteed.

7 CONCLUSIONS

7.1 Summary of the study and main findings

Based on the research, it can be concluded that the market is ready for the implementation of DTs for building performance management. Accordingly, improving the performance of existing commercial buildings is an important facility management task. Some building characteristics, such as the building envelope and its thermal conductivity, remain static. However, other variables such as solar radiation, heating capacity and air quality can be measured and optimized through the use of DTs and smart technologies.

The implementation of a DT for an academic building, capable of analyzing and optimizing data from multiple sources, can reduce energy costs, which in turn improves energy efficiency and also creates a more conducive learning environment for both students and teaching staff – a critical aspect for long-term success. In addition, students interested in Data Analysis and the integration of BIM with DT data can actively contribute to the continuous improvement of this solution.

It should be emphasized that the development of a DT requires extensive collaboration between several entities as well as the comprehensive analysis of large amounts of data, which necessitates the appointment of a data analyst and staff responsible for maintaining and updating the DT as well as the BIM model.

7.2 Contributions and implications for the industry

The findings of this study have practical value for the commercial building sector. The study highlights the potential of digitization in managing energy consumption and equipment maintenance, which can streamline operations and improve efficiency. For example, in a DT scenario, lights and equipment can automatically adjust their states based on occupancy, and at the other scenario sensors can quickly detect faults and alert facility management in the event of an emergency.

7.3 Limitations of the study

The main limitation of the research is the inability to incorporate real sensor data into the DT software. This limitation is due to the challenges associated with procuring, installing, setup and configuring a sensor-based system, which requires significant time, coordination and related activities.

7.4 Recommendations for the future work

In order to further develop this case study, taking into account the limitations of the process mentioned, it is recommended to explore methods for efficiently uploading data from sensors to the DT software, or to consider developing scripts to transform data from Smart Building Cloud Platforms (such as HOBOconnect Monitoring App) into a machine-readable format compatible with the DT software. This will pave the way for more robust and data-driven DT applications for the operation phase.

In addition to the findings of this study, future research efforts could include a comprehensive review of user quality assurance and energy efficiency standards, exemplified by notable frameworks such as the WELL Building Standard and ASHRAE. The WELL Building Standard, with its holistic approach to health in the built environment, covering behavioral, operational and design aspects, remains a promising avenue for further exploration. Similarly, ASHRAE, which provides standardized test methods, recommendations for equipment design and installation, and valuable industry guidance, warrants closer examination in future research efforts. Such kind of standards have the potential to significantly influence and improve building performance, making them “smarter”.

7.5 Final thoughts

In summary, even small measures to optimize energy use in educational buildings can yield significant benefits in terms of both building performance and occupant comfort. These improvements can create a win-win scenario by increasing not only the efficiency of the building, but also the well-being and general productivity of its occupants.

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9 APPENDICES

Appendix 1: Completed checklists from First Floor with information about required actions to be taken and with attached photos;

Appendix 2: Level of Detail Table.

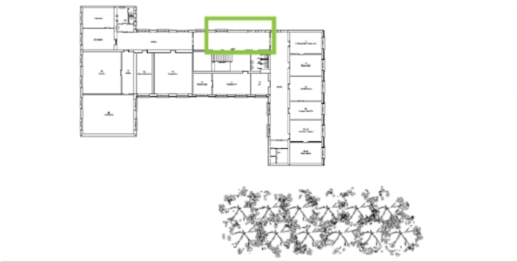
9.1 Appendix 1

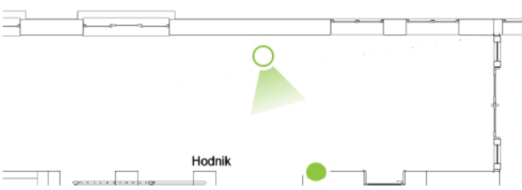
BIMQ10 AS-BUILT QA

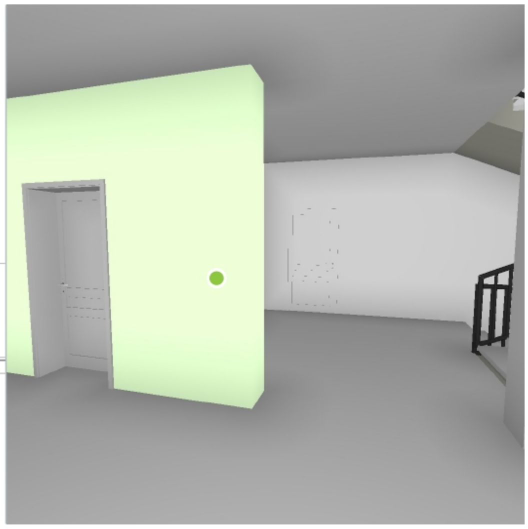
Dalux Field

Printed Sep 22 2023, 10:39 PM
Daria Kharchenko

Project	UL FGG - Inženirski objekti	Created by	Daria Kharchenko
Building	UL FGG - Hajdrihova	Created	May 29 2023, 4:55 PM
Level	Nadstropje 1	Modified by	Daria Kharchenko
Room	Hodnik	Modified	Sep 22 2023, 10:33 PM
3D object category	IfcWall	Status	Completed
3D object	Z - 055		
Zone	Common space		







Actions required	To be changed

Change wall sizes

Changed by Daria Kharchenko, May 29 2023, 4:55 PM

1 - May 29 2023, 4:55 PM

2 - May 29 2023, 4:55 PM

Required changes	Geometry

Changed by Daria Kharchenko, May 29 2023, 4:55 PM

Element	Z - 055

Changed by Daria Kharchenko, May 29 2023, 4:55 PM

Type	Modularna opeka 3618430024 380

Changed by Daria Kharchenko, May 29 2023, 4:55 PM

ID	jGpw5eAZyi9h0OI8x_GZ7A

Changed by Daria Kharchenko, May 29 2023, 4:55 PM

BIMQ12 AS-BUILT QA

Dalux Field

Printed Sep 22 2023, 10:39 PM
Daria Kharchenko

Project	UL FGG - Inženirski objekti	Created by	Daria Kharchenko
Building	UL FGG - Hajdrihova	Created	May 29 2023, 5:04 PM
Level	Nadstropje 1	Modified by	Daria Kharchenko
Room	WC	Modified	Sep 22 2023, 10:33 PM
3D object category	IfcSlab	Status	Completed
3D object	PL - 003		
Zone	Common space		

Actions required	To be added

Add lamp

Changed by Daria Kharchenko, May 29 2023, 5:04 PM

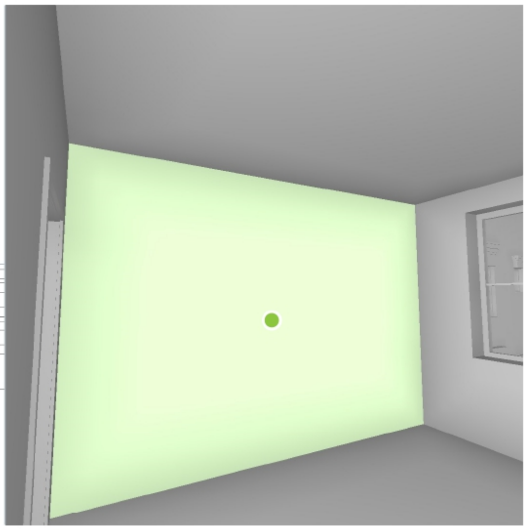
1 - May 29 2023, 5:03 PM

BIMQ13 AS-BUILT QA

Dalux Field

Printed Sep 22 2023, 10:40 PM
Daria Kharchenko

Project	UL FGG - Inženirski objekti	Created by	Daria Kharchenko
Building	UL FGG - Hajdrihova	Created	May 29 2023, 5:06 PM
Level	Nadstropje 1	Modified by	Daria Kharchenko
Room	Predavalnica 17	Modified	Sep 22 2023, 10:33 PM
3D object category	IfcWall	Status	Completed
3D object	Z - 090		
Zone	Common space		



Actions required	To be added
Add furniture, radiator, sink, lamps	

Changed by Daria Kharchenko, May 30 2023, 1:44 PM

1 - May 30 2023, 1:42 PM

2 - May 30 2023, 1:42 PM

3 - May 30 2023, 1:43 PM

4 - May 30 2023, 1:43 PM


5 - May 30 2023, 1:43 PM


6 - May 30 2023, 1:43 PM


7 - May 30 2023, 1:43 PM

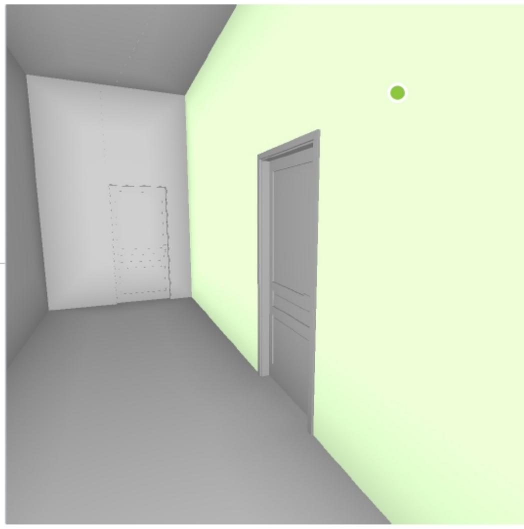

8 - May 30 2023, 1:43 PM

BIMQ15 AS-BUILT QA

Dalux Field

Printed Sep 22 2023, 10:40 PM
Daria Kharchenko

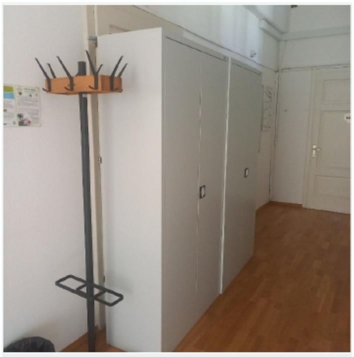
Project	UL FGG - Inženirski objekti	Created by	Daria Kharchenko
Building	UL FGG - Hajdrihova	Created	May 29 2023, 5:14 PM
Level	Nadstropje 1	Modified by	Daria Kharchenko
Room	Hodnik 27	Modified	Sep 22 2023, 10:33 PM
3D object category	IfcWall	Status	Completed
3D object	Z - 102		
Zone	Common space		



Actions required	To be added

Add furniture, sink, lamps, inner windows

Changed by Daria Kharchenko, May 29 2023, 5:14 PM



1 - May 29 2023, 5:13 PM

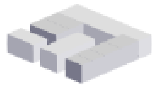
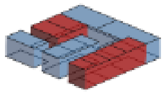
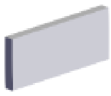
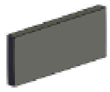
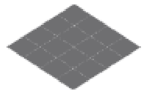
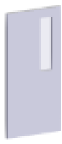
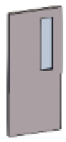
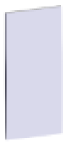
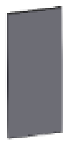
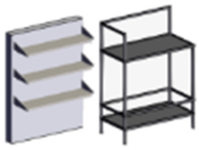
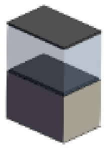
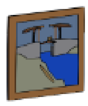
2 - May 29 2023, 5:13 PM

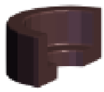
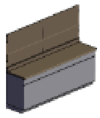
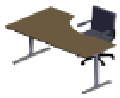
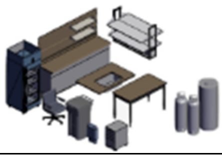
3 - May 29 2023, 5:13 PM

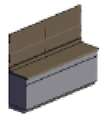
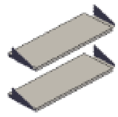
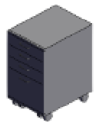
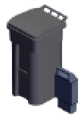
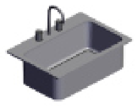
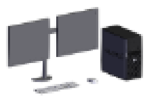
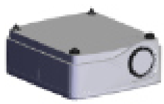
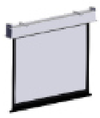
4 - May 29 2023, 5:13 PM

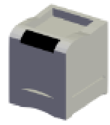
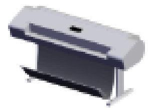
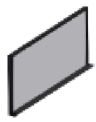
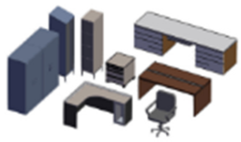
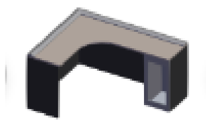
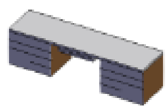
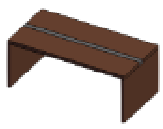
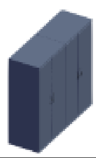
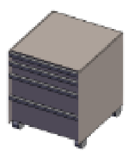
5 - May 29 2023, 5:13 PM

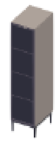
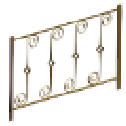
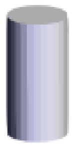
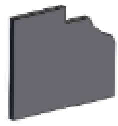
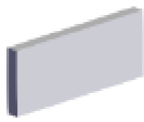
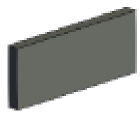
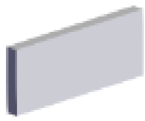
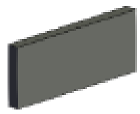
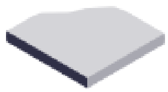
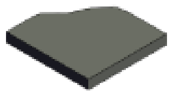
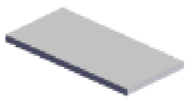
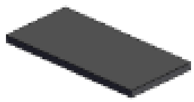
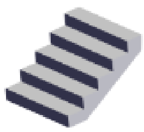
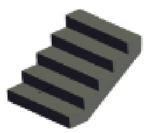
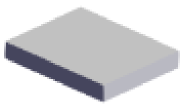
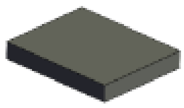
9.2 Appendix 2

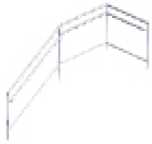
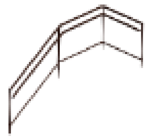
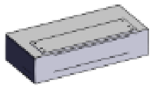
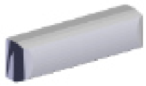
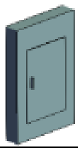
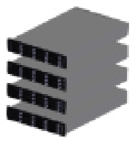
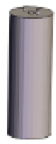
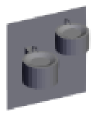
Level of Detail Table	AS-IS		TO-BE	
Project setup				
1. Architecture				
Rooms	200		300	
Partition Walls	200		300	
Ceilings	200		300	
Interior Doors	200		300	
Exterior Doors	200		300	
Windows	200		300	
1.1 Common space				
Inner Curtain Walls	200		300	
Storage Racks and Shelving			300	
Aquariums			300	
Information Boards			300	

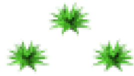
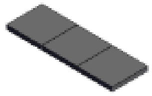
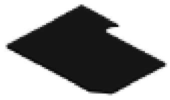
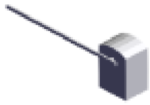
Fixed Seating	300	
Moveable Accessories	300	
1.2 Classrooms and labs		
Educational Furnishings	300	
Classroom Furniture	300	
Classroom Workstations	300	
Classroom Fixed Cabinets	300	
Classroom Movable Cabinets	300	
Classroom Shelving	300	
Other Furnishings	300	
Laboratory Equipment:	300	
Lab Refrigerators	300	
Lab Air/Gas Containers / Tanks	300	
Lab Liquid Containers	300	

Floor Mounted Lab Cabinets	300	
Wall Mounted Lab Cabinets/ Shelves	300	
Lab Mobile Cabinets / Drawers	300	
Lab Chairs	300	
Lab Tables	300	
Lab Disposal Bins	300	
Lab Plumbing Fixtures	300	
Educational Equipment	300	
Classroom White/ Marker Boards	300	
Classroom Computers	300	
Classroom Projectors	300	
Classroom Projection Screens	300	
1.3 Offices and staff spaces		

Office Equipment	300	
Computers	300	
Printers / Copiers	300	
Plotters	300	
Marker Board	300	
Office Furnishings	300	
Workstation Desks	300	
Workstation Chairs	300	
Workstation Cabinets / Millwork	300	
Work / Drafting Tables	300	
Fixed / Millwork Cabinets	300	
Movable File Cabinets	300	

Fixed File Cabinets			300	
Personal Clothing Lockers			300	
1.4 Architectural details				
Decorative Railings			300	
2. Structure				
Concrete Columns	200		300	
Exterior Walls	200		300	
Precast Walls	200		300	
Parapet Walls	200		300	
Floor Slabs	200		300	
Roofs	200		300	
Concrete Stairs	200		300	
Concrete Stair Landings	200		300	

Concrete Stair Railings	200		300	
3. MEP Systems				
3.1 Mechanical systems				
HVAC Equipment			300	
Split System Air Conditioners			300	
3.2 Electrical systems				
Lighting Fixtures			300	
Electrical Panels and Switchboards			300	
Emergency Lighting Fixtures			300	
Data Equipment Servers			300	
3.3 Plumbing systems				
Plumbing Fixtures	200		300	
Water Heaters			300	
Drinking Fountains			300	
4. Landscaping				
Landscaping	200		300	

Existing Site Vegetation	200		300	
Roadways	200		300	
Pedestrian Walkways	200		300	
Parking Pavement	200		300	
Parking Entrance Barrier			200	
Site Lighting			200