Digital Twins for Optimizing Facility Management and Retrofitting in Existing Buildings - Infrastructure Preparations and Challenges

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Abstract

The construction sector has significant potential for energy savings compared to other manufacturing sectors. The operation of buildings significantly contributes to global energy consumption and greenhouse gas emissions. Optimizing facility management and retrofitting, particularly through digital twins (DTs), offers a solution to reduce the environmental impact of building operations without an extensive need of resources. The main challenge lies in existing buildings, where information is often incomplete. Creating DTs for existing buildings involves defining and collecting necessary data using methods such as photogrammetry, laser scanning, and sensor technologies. By integrating sensor data into the static data of the DT, predictive maintenance, improved space utilization, enhancements in user behavior, and a better basis for decision-making by retrofitting measures can be achieved. This paper outlines the infrastructure requirements and challenges of creating DTs for various use cases using real-world examples and provides valuable insights for future research in this field.

Keywords: Digital twin, BIM, IoT, sensor technology.

1. Introduction

The operation phase of an asset, typically around 80 years, requires more resources and costs than the planning and execution phases (Lu et al 2019, BuildingSMART a 2024). During this phase, decisions on retrofitting, maintenance, space management, and energy efficiency are essential. Access to digital structural and dynamic lifespan data is crucial for informed decision-making.

BIM method (Building Information Modeling) is used mostly in the planning and less in the execution phases of new building projects. BIM is rarely used in the operation phase. Even CAFM tools (Computer Aided Facility Management) are not used for all existing building in the EU (Krämer et al 2023).

When it comes to deciding on retrofitting in existing buildings, decision-makers are facing increasing uncertainty. This uncertainty impacts both the anticipated costs and construction timelines, often leading to a preference for new construction over retrofitting. Although, retrofitting measures for buildings often present not only more environmentally friendly but also cost-effective solutions compared to new construction in terms of resource utilization (Federico 2023).

A significant portion of the buildings in the EU, exceeding 80%, predates 1990 (Economidou et al 2011), emphasizing a lack of reliable foundation, whether in physical or digital form, for planning and executing necessary maintenance or structural alteration measures. In today's context, access to accurate and reliable data, ideally structured and interconnected in digital formats, is paramount for effective operation and construction activities in existing buildings.

For sustainable, economical, and conscientious decision-making in existing buildings, the creation of DTs is crucial. This raises questions about which use cases can be addressed by a DT, what basic information is required for its creation, how this information should be collected and managed, and which challenges exist in utilizing this data. This paper presents findings from a third-party funded project that investigated these topics using real existing buildings.

2. Digital Twin for existing buildings

A DT of an existing building refers to a virtual replica of the physical building or asset that continuously sync with their real-world counterpart through sensors and data streams (Deng et al 2021, Lu et al 2019, Tagliabue et al 2021). Using DT allows for a real-time, data-driven approach to managing buildings and facilities.

2.1 Advantages of using digital twins

Using a DT has several advantages. Some of them can be listed in the following points:

- **Predictive maintenance**: DTs enable facility managers to predict maintenance needs and issues before they occur, reducing downtime and extending the lifespan of equipment (Agostinelli & Heydari 2022).
- **Energy efficiency**: By simulating different scenarios and analyzing data in real-time, a DT can optimize energy consumption in buildings, leading to cost savings and sustainability benefits.
- **Improved decision-making**: Real-time data from DTs provides valuable insights for better decision-making regarding building operations, resource allocation, and occupant comfort.
- **Enhanced safety and security**: Monitoring building conditions through DT allows for the early detection of safety or security risks, ensuring a safer environment for occupants.
- **Remote monitoring and control**: DTs enable remote monitoring and control of building systems, allowing facility managers to adjust settings and respond to issues promptly without physical presence.
- **Education**: The integration of data sets acquired through DTs significantly enriches teaching methodologies, including hands-on simulations, virtual labs, and real-time case studies, enhancing and promoting experiential learning at the university level.

2.2 Difficulties by creating digital twins for existing buildings

In contrast to new construction projects in which BIM models are developed, sensors are installed, and an as-built model is handed over to the building operators at the end of the construction phase, the situation with existing buildings is different. Creating a DT for an existing building can indeed pose challenges due to the lack of comprehensive and accurate information about the building's design, construction, and operation history. Moreover, incorporating data from various sources into a cohesive DT model can be challenging due to compatibility issues, different data silos, and inconsistencies. The main key factors contributing to the difficulty of creating a DT for existing buildings can be outlined in the following points:

- **Incomplete or inaccurate static data**: Existing buildings may lack detailed documentation or as-built drawings, making it challenging to capture the accurate geometry, material specifications, and equipment details required for creating a reliable DT.
- **Legacy systems and data silos**: Older buildings may have legacy Building Automation System (BAS) or Building Monitoring System (BMS) in place that do not easily integrate with modern Internet of Things (IoT) devices or IoT platforms.
- **Heterogeneous data sources**: Data about existing buildings may be dispersed across various sources, formats, and levels of detail, including paper records, digital files, equipment manuals, and maintenance logs. Integrating this heterogeneous data into a cohesive DT model can be complex and time-consuming.

2.3 IoT for digital twins of existing buildings

Sensor technology uses sensors to measure specific changes, converting these measurements into electrical signals for data collection and processing. Actuators use these signals to correct detected behaviors.

MEMS technology (micro-electromechanical systems) allows for compact sensors, making them convenient for existing buildings.

The average sales prices for sensors have shown a consistent downward trend between 2015 and 2020, with a forecast Compound Annual Growth Rate (CAGR) of -8 percent (Nölling 2017). This decrease in prices has made it increasingly feasible to implement IoT technologies in existing buildings, opening up new opportunities for enhanced connectivity and smart applications. However, the disruptions in supply chains and logistics caused by the mitigation measures of the COVID-19 pandemic led to a global chip shortage between 2020 and 2023, resulting in price increases and extended ordering processes.

Used sensors for recording life data in buildings to support DT can be categorized in following groups:

- Environmental sensors: These sensors measure parameters such as temperature, relative humidity (RH), smoke, carbon dioxide, carbon monoxide, and lighting levels to assess indoor environmental quality and optimize occupant comfort.
- Energy meters and submeters: These sensors are used to monitor electricity, water, gas, or HVAC system consumption, enabling precise energy management, cost analysis, and identification of energy-saving opportunities.
- Equipment health sensors: These embedded sensors in building equipment and systems (e.g., motors, pumps, HVAC units) can track e.g. vibrations, temperature, pressure, and other indicators of asset health to support predictive maintenance and performance optimization.
- Occupancy sensors: These sensors detect the presence, movement and number of occupants in different building areas, enabling efficient space utilization, lighting control, and HVAC adjustments based on real-time occupancy patterns. Moreover, they can be used for security monitoring by detecting human presence and movement within the building premises.

These sensor groups, when integrated with DT, provide a comprehensive data-driven approach for monitoring, analyzing, and optimizing building performance and operations based on real-time life data feedback.

Multi-sensors can measure multiple values simultaneously. These sensors are particularly useful for increasing efficiency and reducing costs, as they can combine multiple functions in one device (Lingbao et al 2020). An example of a multi-sensor is an environmental sensor that can simultaneously measure temperature, RH, and air quality. This type of sensors can be used in residential and non-residential buildings to monitor indoor climate and detect potential issues early on.

Sensors may be integrated into an IoT (Internet of Things) system where internet connectivity is needed for data transmission and remote monitoring. To integrate into IoT system, each sensor – and therefore each device equipped with it – is assigned its own identity.

The collected IoT data can serve various communication purposes, such as facilitating interactions between humans and machines (Human Machine Interface: HMI). For instance, this might involve sending notifications or providing recommendations for action through channels like email or similar means. Alternatively, the data can enable communication between machines (Machine to Machine interface: M2M), facilitating processes such as transferring sensor information to control actuators.

2.4 Network types for data communication between IoT devices

There are different types of networks used for data communication within a DT of a building:

- **Ethernet**: this is a popular wired network technology that uses cables to connect devices within a network. However, it may not be well-suited for subsequent installation in existing buildings.

- **WLAN** (Wireless Local Area Network): this is a type of wireless network that allows devices to connect to a local area network using radio waves instead of cables.
- **LPWANs** (Low-Power Wide Area Networks): such as NB-IoT, SigFox and LoRaWAN are designed for long-range communication with low power consumption. These technologies are often used for IoT applications, where devices need to communicate over long distances while conserving battery life. For example, LoRaWAN (Long Range Wide Area Network) is a protocol designed for communication between IoT devices and gateways (Bankov et al 2016). The network architecture is based on a star-of-stars topology, where end devices communicate with gateways that forward data to a central network server. One of the key features of LoRaWAN is its ability to support bi-directional communication, allowing devices to not only transmit data but also receive commands and updates from the network. However, extensive planning and deployment of LoRaWAN sensors and gateways may be required to ensure adequate network coverage.

2.5 Used Network Protocols and data formats

In the realm of the IoT, various protocols are commonly utilized for facilitating data exchange among interconnected devices and systems. Some of the most widely used protocols include:

- **HTTP** (Hypertext Transfer Protocol) is common for web-based IoT services.
- **MQTT** (Message Queuing Telemetry Transport) is a lightweight messaging protocol ideal for constrained IoT devices and unreliable networks (OASIS 2019).
- **OPC UA** (Open Platform Communications Unified Architecture) is a standard protocol commonly used in industrial IoT applications (Mahnke & Leitner 2009).
- **Modbus** is a protocol commonly used to establish communication in industrial automation systems (The Modbus Organization 2012).

In terms of data formats, IoT devices often use lightweight protocols such as JSON (JavaScript Object Notation) and XML (eXtensible Markup Language) to transmit data in a structured and easily readable manner. JSON is commonly used for building REST APIs and communicating data in IoT applications (ISO/IEC 21778 2017). Its lightweight, simplicity, and readability make it a preferred choice to utilize within various protocols such as MQTT to structure exchanged messages. IoT devices can publish JSON-formatted data to MQTT topics, enabling subscribers to consume and process the information.

These data formats allow IoT applications to process, analyze, and act upon the information collected from connected devices in a seamless manner.

3. Databases for digital twin data

Databases are crucial for storing, managing, and retrieving organized data efficiently. They provide structured storage for easy access and manipulation, aiding in informed decision-making and improving operational efficiency. A relational database is a data storage system that organizes data into tables with rows and columns. These tables are interconnected through common fields, enabling efficient data querying and manipulation. Relational databases utilize Structured Query Language (SQL) for data interaction. However, relational databases may encounter scalability challenges by the management of substantial data volumes generated by IoT devices, potentially leading to performance bottlenecks when processing high-velocity IoT data.

To efficiently handle time-stamped data, organizations often turn to alternative solutions such as NoSQL databases (Grolinger et al 2013) or time series databases (Namiot 2015). These alternatives excel in storing, querying, and analyzing time-based data, which is crucial for time-sensitive applications requiring high-performance data processing. Time series databases are dedicated to managing time-stamped data effectively. They enable swift data ingestion, support time-based queries, and provide specialized tools for time-series analysis. Widely adopted in IoT and monitoring systems, time series databases like the popular open-source InfluxDB prove invaluable for uncovering insights from temporal data. NoSQL databases, such as the well-known open-source Apache Cassandra, offer a flexible and scalable approach to data management. Unlike traditional relational databases, NoSQL databases do not have fixed schemas, allowing for the storage of unstructured, semi-structured, and structured data types. Geared towards handling vast data volumes and rapid data streams, NoSQL databases are extensively used in big data analytics projects.

Dashboards can be implemented to visualize and analyze the collected metrics in the database using graphs, charts, and tables in real-time. This enables users to monitor their systems and gain a better understanding of their performance. For this purpose, open-source visualization, and monitoring platforms such as Grafana (Grafana 2024) can be used in conjunction with time-series databases like InfluxDB. However, such dashboards are integral parts of each commercial IoT platform.

4. IoT platforms

For device connectivity, data management, analytics, and visualization different commercial IoT Platforms can be used for IoT deployments, for example:

- **AWS IoT Core (Amazon Web Services)**
- **Microsoft Azure IoT Hub**
- **IBM Watson IoT Platform**
- **Cisco IoT Cloud Connect**
- **ThingsBoard:** is an open-source scalable IoT platform that can handle many devices and data streams (ThingsBoard 2024). It allows users to easily onboard, configure, and manage IoT devices from a centralized dashboard. Moreover, it includes a rule engine that enables users to define complex event processing rules, automate actions based on triggers, and generate alerts and notifications. ThingsBoard supports a variety of data protocols for data ingestion and integration with IoT devices and systems such like MQTT, OPC UA or Modbus. ThingsBoard uses the NoSQL database Apache Cassandra as its primary database for storing and managing IoT data and configurations.

5. Project description and implementation

As part of a third-party funded project between 2019 and 2023, a platform is being set up for six representative university buildings (institutional buildings) with heterogeneous types of use on the campus of the University of Applied Sciences in Lübeck, Germany, in which comprehensive operational, usage, and weather data, together with information on building construction and technical equipment, are merged in digital building twins. Different methods were used for the modelling of the static structure of the buildings as the quality of the available documents and plans, if any, varies significantly.

For well-documented buildings, the plans and the construction description from the facility management department were used. Additionally, the details were verified for consistency through on-site inspections in the buildings.

For buildings without available or outdated documents, surveying techniques such as laser scanning, or photogrammetry were used to create point clouds from the existing building and generate a 3D model. In this case, the level of detail of the collected information is limited to the surfaces of the components, without being able to determine information about, for example, wall and ceiling constructions. However, since this information is essential within the scope of the considered use cases in this project, it was necessary to gather additional information that could not be determined by the mentioned measurement methods. Unfortunately, the project team was not allowed to conduct core drillings. Therefore, non-destructive material testing was used to determine further properties of the components, such as the thermal transmittance of the walls or the rough position of hidden components (e.g. pipes, ducts, etc.).

Creating a BIM model of the existing building involves integrating relevant architectural, structural, and MEP (Mechanical, Electrical, Plumbing) information. Additionally, this process entails incorporating sensor objects, their locations, and metadata attributes to align sensor data with specific building elements.

The sensor density depends on the specific data to be collected and the type of rooms. Through the developed placement concept in the project a higher sensor density is planned in high-traffic areas such as meeting rooms, while a lower level of sensor deployment was required in less frequented areas.

The sensor placement concept involves as well identifying the key parameters and performance indicators that require monitoring in each room and for each component, such as temperature, RH, occupancy, and energy consumption. This concept also encompasses determining the suitable type and placement of sensors based on the data requirements and areas of interest within the building (figure 1).

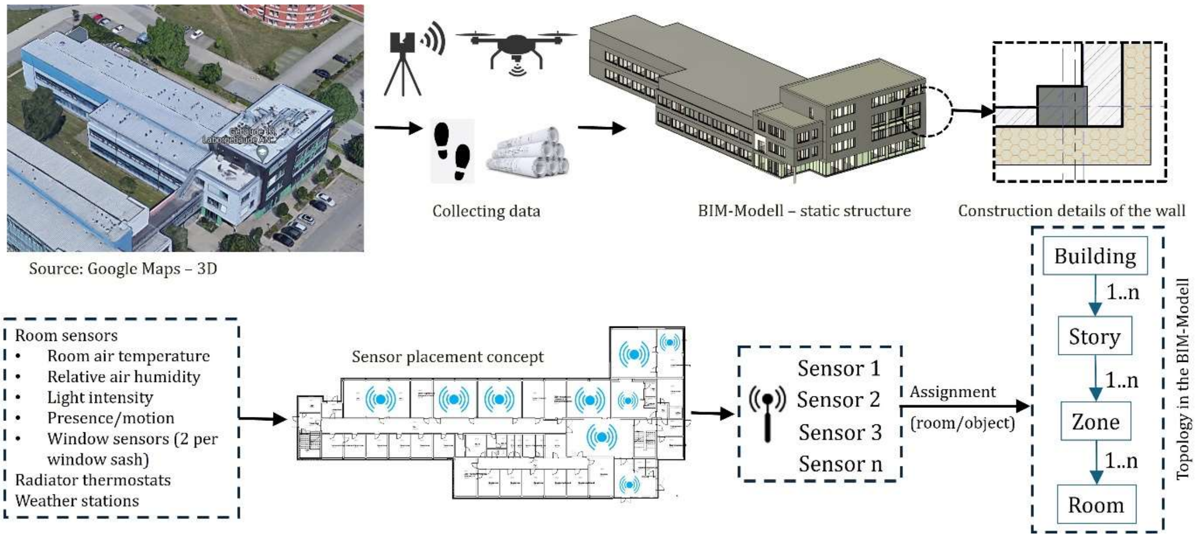


Figure 1: Assignment of different sensor types to the static components of the BIM model of the existing building.

The sensors are integrated as simple geometry in the BIM model. Additionally, the geometry of the sensor is augmented with alphanumeric data intended to capture details about the sensor itself and the measured values. To achieve this, the available information in the IFC documentation of IFC4 was initially reviewed, including entities like IfcSensor, IfcSensorTypeEnum, and various relevant Property Sets (Psets). Over 50 different and relevant Psets were examined on the BuildingSmart website (BuildingSMART b 2024). Some of these Psets indeed contain necessary properties for the sensors in the project, such as Pset_EnvironmentalCondition (including ReferenceAirRelativeHumidity and Reference-EnvironmentTemperature), Pset_Environmental-Emissions (including CarbonDioxide-Emissions), Pset_InstallationOccurrence (including InstallationDate), and Pset_Manufacturer-TypeInformation. The IfcSensor entity is too general and lacks specific information required for the defined use cases in the project. The IfcSensorTypeEnum class offers a range of possible sensor types, like CO2SENSOR or TEMPERATURESENSOR. A multi-sensor can be classified as USERDEFINED one in any case.

As a focused and streamlined implementation of the requirements, a custom Pset called IoTSensor was developed in the project to encompass information about the manufacturer, installation, and measured values of a multi-sensor. In table 1 the implemented parameters and data types of the Pset (IoTSensor) are shown.

The deployment of the IoT sensor network for collecting real-time data on the identified parameters involves utilizing a LoRaWAN architecture. LoRaWAN was selected for this project for a variety of reasons. The wireless network is well-suited for installation in existing buildings and offers the advantage of long-distance communication with low power consumption. Moreover, the public utility company in Lübeck has already implemented a LoRaWAN infrastructure for the smart city. The signal strength around the campus is adequate for establishing a LoRaWAN network for the DTs and seamlessly integrating it with the existing infrastructure of the public utility company.

The LoRaWAN sensors, which are battery-operated and wirelessly connected to the LoRaWAN network through gateways, include a.o. multi-sensors for monitoring the environment in the rooms, windows and doors reed switch sensors and radiator thermostats.

Table 1. Parameters of the Pset (IoTSensor) of the entity IfcSensor

Parameter	Data type	Unit
ID	real	-
Manufacturer	string	-
Model	string	-
Building	string	IfcGloballyUniqueId
Space	string	IfcGloballyUniqueId
Component	string	IfcGloballyUniqueId
Temp	real	°C
RH	percentage	-
CO2	real	PPM
IlluminationIntensity	real	lux
Motion	boolean	-
Contact	boolean	-
InstallationDate	real	epoch nanosecond
BatteryVoltage	real	volt
BatteryChange	real	epoch nanosecond

Various rules are implemented to determine the status of the components. For instance, two sensors are used for each window sach to ascertain whether the window is open, tilted, or closed based on the measured values of the parameter “contact” in table 1. If both values are true, this means the window is closed. If both values ae false, this means the window is open. If the sensors' contact values differ (true/false), this indicates that the window is tilted.

The number of people in a room can significantly affect the expected internal heat gains and overall comfort, such as high RH or elevated carbon dioxide concentrations. Therefore, it is recommended to monitor the occupancy of meeting rooms, seminar rooms, and lecture rooms. To achieve this, optical sensors certified by EuroPriSe are utilized. These sensors analyze the current image to detect head and shoulder formations through an algorithm. It is important to note that no personal data is stored or shared in this process (EuroPriSe 2024).

Alle these sensors send MQTT messages to the gateways or receive messages wirelessly back from them. The implemented gateways are mounted outdoors on the rooftops of the building, with each gateway registered to a LoRaWAN network server through configuration settings. In operation, a gateway receives LoRa messages from end devices and forwards them to the LoRaWAN network server, which is managing the entire network. The network server handles tasks such as message deduplication, ensuring that only a single copy of a message is retained if multiple copies are received (figure 2).

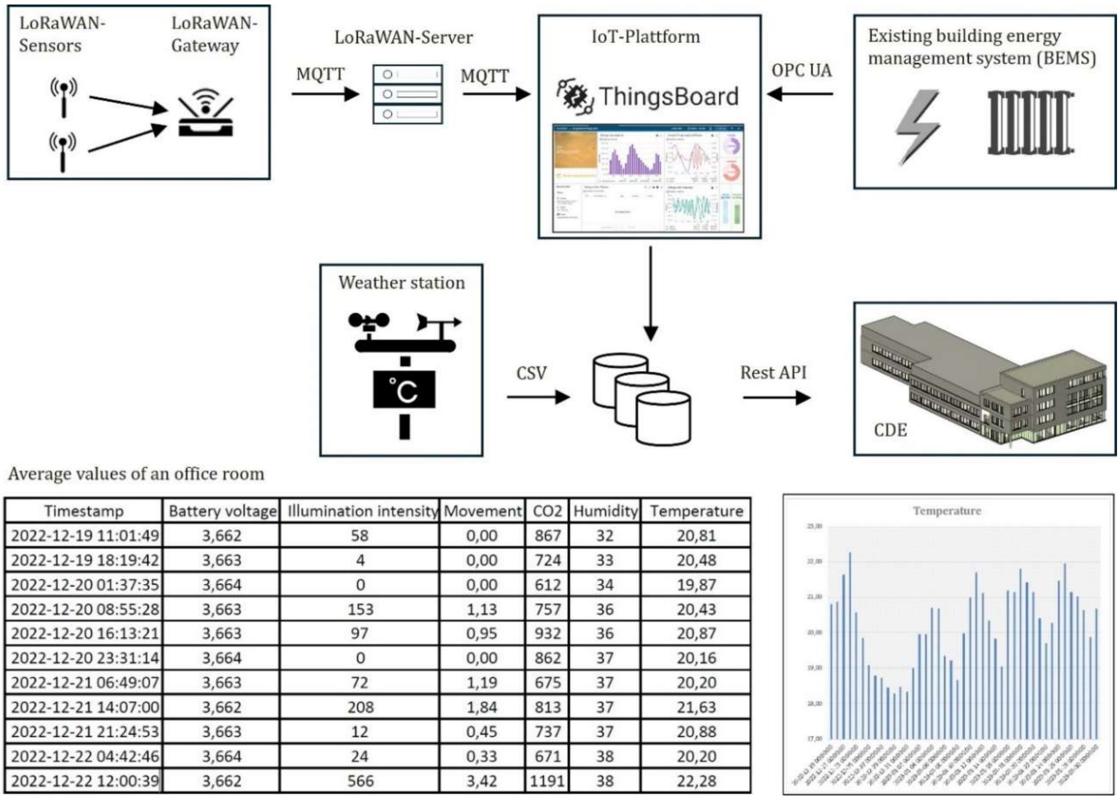
An excerpt of the measured values for an office room are shown in the table in figure 2. Each column in the table represents a measurement parameter and each row represents a time-stamped measurement case of all parameters in the office room as an ordered sequence of observations (i.e. time series). A data set of one office room and the IFC model of the corresponding building can be found under (Sharmak 2024).

A REST API is utilized to facilitate the exchange of metrics from IoT sensors according to the Pset (IoTsensor) with the Common Data Environment (CDE) tool of the project. IoT devices transmit their data to the network server using the MQTT protocol. The network server then exposes this data through a RESTful API, enabling access by the CDE tool through a user-defined script. Integrating IoT sensor data with the BIM model hosted in the CDE allows for real-time visualization of sensor data on the BIM model to reflect the current conditions and performance metrics within the building.

However, for the visualization of long-term data, maintenance, and monitoring decisions, leveraging the capabilities of the used IoT Platform proves to be more practical. CDE tools typically do not provide the necessary functionalities for managing DTs.

6. Challenges in the implementation

Developing and maintaining DTs, especially for existing buildings, involves investments in technology, infrastructure, software licenses, and ongoing maintenance. Creating BIM models can be complex due to the lack of diverse needed information in construction and inspection documents. Additionally, non-destructive material testing has been found to be inefficient. For example, determining the thermal transmittance of an external wall with unknown materials and thickness of each layer requires several days of testing and a temperature difference of at least ΔT=15K between indoor and outdoor temperatures.



Average values of an office room

Timestamp	Battery voltage	Illumination intensity	Movement	CO2	Humidity	Temperature
2022-12-19 11:01:49	3,662	58	0,00	867	32	20,81
2022-12-19 18:19:42	3,663	4	0,00	724	33	20,48
2022-12-20 01:37:35	3,664	0	0,00	612	34	19,87
2022-12-20 08:55:28	3,663	153	1,13	757	36	20,43
2022-12-20 16:13:21	3,663	97	0,95	932	36	20,87
2022-12-20 23:31:14	3,664	0	0,00	862	37	20,16
2022-12-21 06:49:07	3,663	72	1,19	675	37	20,20
2022-12-21 14:07:00	3,662	208	1,84	813	37	21,63
2022-12-21 21:24:53	3,663	12	0,45	737	37	20,88
2022-12-22 04:42:46	3,664	24	0,33	671	38	20,20
2022-12-22 12:00:39	3,662	566	3,42	1191	38	22,28

Figure 2: The architecture of the implemented DT project.

One of the use cases in this project is the energy performance simulation and the comparison between the actual and target data in this field. The used software for thermal building simulation (a market leader in this area) allows the import of IFC files. A specific modelling guideline must be followed when creating the architectural model to even enable the use of its IFC model. The architectural model created for this purpose is too abstract and unsuitable for other use cases in the project. This leads to the need to create multiple models for different use cases, resulting in significant time wasted in the information modeling. Similar issues regarding problems in the efficiency and compatibility in this interface between architecture and simulation have also been reported in (Katranuschkov et al. 2014).

Due to the COVID-19 pandemic and the associated chip shortage, sensors could only be procured and deployed late and at an expensive price. This led to a delay in the entire duration of the project.

Ensuring compliance with the principles of data protection set forth in the General Data Protection Regulation (GDPR, EU 2016/679), including data minimization, transparency, explicit consent, and anonymization, is paramount when collecting data through DTs of buildings. A careful balance must be struck between the data protection rights of employees and building visitors, the advantages of enhanced efficiency, resource conservation, and user-friendliness, and the legitimate interests of researchers by developing and usage of DTs. Despite the thorough consideration given to these aspects in the project, a small percentage of employees (less than 5%) have declined the installation of sensors in their office rooms, citing concerns about the safeguarding of their personal data. Such refusal presents a challenge in gaining a comprehensive understanding of the overall situation within the designated building.

7. Conclusions and future work

Creating DTs for existing buildings involves challenges such as large investments and ongoing costs. Personal data protection must be considered when processing and using data. Problems at the interfaces between different systems still exist and workarounds are still needed. Nevertheless, DTs offer the digital basis for a conscious decision in the operation phase of a building.

The current state of development allows to indicate, based on real-time measurements, when, for example, the CO2 levels in the room are too high and manual ventilation is necessary, or when the RH in the room is too high, which could pose a risk of mold formation. In this case, it is possible to establish a dew point rule based on the measured values of air temperature and RH in the outdoor and indoor areas, which triggers the activation of the mechanical ventilation systems.

A conclusion about a snapshot of a single value of a measurement point or the data of a single measurement point collected over a long period of time does not pose a major challenge. For example, using linear regression, it is possible to predict a trend in the development of a measurement value for an equipment, enabling predictive maintenance strategies that help prevent unexpected failures, reduce downtime, and extend equipment lifespan.

A conclusion regarding the current situation based on the measured values of different measurement points and components over an extended period in combination with the physical and geometric properties in the BIM model and the weather data is still pending. An exemplary snapshot of the measurement values in an office can be found in Table 2. Only the measurement values over a long period can help, for example, to identify a trend or to depict occupancy patterns. The development of data mining and artificial intelligence methods are still necessary for analysing this large amount of data of various origins at the building level, as reported by (Carlucci et al 2020, Sun et al 2020, Sacks et al 2020).

Table 2: A snapshot about all the collected values of the measurement points in an office room

Time stamp	**Window 1**	**Window 2**	**Door**	**Persons**	**CO2 (ppm)**	**Temp inside (°C)**	**RH inside**	**Temp. outside (°C)**	**RH outside**	**Light (Lux)**
xxx	Closed	Tilted	Closed	3	1132	21,3	62%	11,7	43%	420

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References

Agostinelli, S. & Heydari, A. (2022). Digital twin predictive maintenance strategy based on machine learning improving facility management in built environment. 10.1016/B978-0-12-820793-2.00007-0.

Bankov D., Khorov E. & Lyakhov A. (2016). On the Limits of LoRaWAN Channel Access. 2016 International Conference on Engineering and Telecommunication. Russia. pp. 10–14. doi:10.1109/ent.2016.011. ISBN 978-1-5090-4553-2. S2CID 44799707

BuildingSMART (2024 a). The Built Asset Industry. https://education.buildingsmart.org/entry/the-built-asset-industry. Retrieved 2024-5-15

BuildingSMART (2024 b). IFC 4.3 ADD2 ISO 16739. https://standards.buildingsmart.org/IFC/RELEASE/IFC4_3/HTML/lexical/IfcSensor.htm

Carlucci, S., De Simone, M. & Firth, S. K. (2020). Modeling occupant behavior in buildings. Building and Environment, vol. 174.

Deng M., Menassa C., Kamat V. R. (2021). From BIM to digital twins: a systematic review of the evolution of intelligent building representations in the AEC-FM industry, ITcon Vol. 26, Special issue Next Generation ICT - How distant is ubiquitous computing?, pg. 58-83, https://doi.org/10.36680/j.itcon.2021.005

Economidou, M., Laustsen, J., Ruyssevelt, P., Staniszek, D., Strong, D. & Zinetti, S. (2011). Europe's Buildings Under the Microscope — A Country-by-country Review of the Energy Performance of Buildings, Buildings Performance Institute Europe (BPIE).

EuroPriSe (2024). https://euprivacyseal.com/en/

Federico, John. (2023). Estimating Construction Costs for Retrofitting Existing Buildings. Zeitschrift für Sprachwissenschaft. 2. 2.

Grafana Labs (2024). https://grafana.com/

Grolinger, K., Higashino, W. A., Tiwari, A. & Capretz, M. (2013). Data management in cloud environments: NoSQL and NewSQL data stores. Journal of Cloud Computing: Advances, Systems and Applications 2013, 2:22

ISO/IEC 21778 (2017). Information technology. The JSON data interchange syntax.

Katranuschkov, P., Scherer, R., Weise, M. & Liebich, T. (2014). Extending BIM for energy simulation and design tasks. Computing in Civil and Building Engineering (2014): 625-632.

Krämer, M., Bender, T., Bock, N., Härtig, M., Jaspers, E., Koch, S., Opić, M. & Schlundt, M. (2023). IT Environments for BIM in FM. 10.1007/978-3-658-40830-5_4.

Lingbao, K., Xing, P., Yao, C., Ping, W. & Min, X. (2020). Multi-sensor measurement and data fusion technology for manufacturing process monitoring: a literature review. International Journal of Extreme Manufacturing. **2** 022001 DOI 10.1088/2631-7990/ab7ae6

LoRa-Alliance. (2024). https://lora-alliance.org/. Retrieved 2024-05-10

Lu, Q., Parlikad, A. K. , P. Woodall, P., Xie, X., Liang, Z., Konstantinou, E., Heaton, J. & Schooling, J. (2019). "Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus." 36(3): 05020004.

Mahnke, W. & Leitner, S.H. (2009). OPC Unified Architecture – The future standard for communication and information modeling in automation. ABB Review 3/2009, page 56-61. https://library.e.abb.com/public/75d70c47268d78bfc125762d00481f78/56-61%203M903_ENG72dpi.pdf. Retrieved 2024-05-05

Namiot, D. (2015) Time Series Databases. In: Proceedings of the XVII International Conference «Data Analytics and Management in Data Intensive Domains» (DAMDID/RCDL’2015), Obninsk, Russia.

Nölling, K. (2017). Smart strategies for smart sensors - Capturing value in next-generation technology. ROLAND BERGER GMBH. Page 4. Available under: www.rolandberger.com/publications/publication_pdf/roland_berger_smart_sensors.pdf. Retrieved 2024-05-05

Oasis Open (2019): Message Queuing Telemetry Transport (MQTT) Version 5.0". Retrieved 20.04.2024: https://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html. Retrieved 2024-2-15

Sacks, R., Girolami, M. and Brilakis, I. (2020). Building Information Modelling, Artificial Intelligence and Construction Tech, Developments in the Built Environment, Volume 4, 2020, 100011, ISSN 2666-1659, https://doi.org/10.1016/j.dibe.2020.100011.

Sharmak, W. (2024). IFC-model of an existing building and datasets of the sensor values of an office room. https://github.com/wsharmak/dt

Sun, L., Shang, Z., Xia, Y., Bhowmick, S. & Nagarajaiah, S. (2020). Review of Bridge Structural Health Monitoring Aided by Big Data and Artificial Intelligence: From Condition Assessment to Damage Detection. J. Struct. Eng. 146, 04020073. https://doi.org/10.1061/(ASCE) ST.1943-541X.0002535.

Tagliabue, L. Cecconi, C., F. R., Maltese, S., Rinaldi, S., Ciribini, A. L. C. & Flammini, A. (2021). Leveraging Digital Twin for Sustainability Assessment of an Educational Building. **13**(2): 480.

The Modbus Organization. (2012). MODBUS Application Protocol specification V1.1b3. https://www.modbus.org/docs/Modbus_Application_Protocol_V1_1b3.pdf. Retrieved 2024-04-15

ThingsBoard. (2024). https://thingsboard.io/. Retrieved 2024-03-12