Towards Concepts for Climate and Energy-Oriented Digital Twins for Buildings

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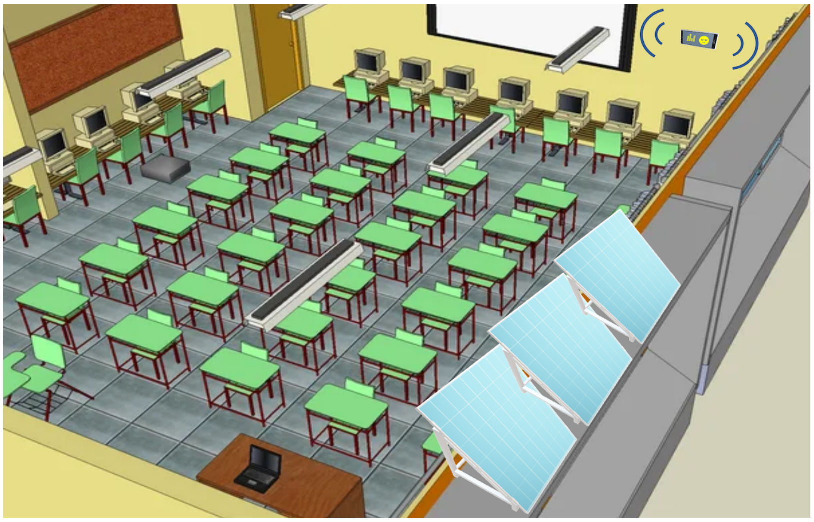

Figure 1: Illustration of a prototype classroom equipped with climate sensors and sustainable energy systems.

ABSTRACT

This paper presents concepts and approaches towards a climate and energy oriented digital twin for public buildings. The sustainable, resource-efficient operation of these buildings, such as schools and education centers, and the monitoring, control, and optimization of their climate, air, and energy performance pose multiple challenges, in particular to cope with the consequences of climate change and changes in the energy economy. In our approach, we consider buildings in which a network of heterogeneous sensors in each spatial unit records key properties such as temperature, humidity, and CO_2 concentration, as well as energy consumption and solar energy production. The continuously collected sensor data forms a spatio-temporal data space, which is used by the digital twin as a basis for AI-based analyses and simulations. The transfer of time-series data in near real time can be done by different databases. Analysis techniques focusing on time-series data allow for targeted access to the information and support the identification of exceptional events, recurring patterns, and the comparison of energy and climate-related performance. A prototype of an energy- and climate-oriented digital twin is currently being implemented in a government project in Andalusia, Spain, covering about 430 public buildings.

CCS CONCEPTS

• **Information systems** → **Information systems applications**; **Geographic information systems**; **Location based services**; **Data streaming**;

Web3D '23, October 09–11, 2023, San Sebastian, Spain

ACM ISBN 979-8-4007-0324-9/23/10.
https://doi.org/10.1145/3611314.3616066

KEYWORDS

Digital Twins, Smart Building, BIM, Energy Efficiency, Domotics, Sensor Data, Data Visualization, GIS

ACM Reference Format:

Salvador Merino, Francisco Guzmán, Jürgen Döllner, Javier Martínez, Rafael Guzmán, and Juan de Dios Lara. 2023. Towards Concepts for Climate and Energy-Oriented Digital Twins for Buildings. In *The 28th International ACM Conference on 3D Web Technology (Web3D '23), October 09–11, 2023, San Sebastian, Spain.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3611314.3616066

1 INTRODUCTION

The sustainable, safe and health-ensuring design and operation of public buildings, such as schools and educational centers, and the monitoring, optimization and documentation of their air and energy footprints are important future challenges to address with the changes and consequences of climate change, energy costs, and environmental impacts [Asif and Zeeshan 2020; Hafez et al. 2023; Wang and Adeli 2014]. In this article, we explore challenges, design, implementation and operation of a prototype of a digital twin (DT) for public buildings (Fig. 1), focusing on their climate and energy-related properties as the first-class functionality to be provided.

1.1 Energy and Climate Characteristics

The *energy and climatic characteristics of buildings* become more and more critical due to various reasons:

- *Climate Change*: Buildings contribute significantly to global greenhouse gas emissions through their consumption for heating, cooling, and electricity.
- *Energy Security and Resilience*: Buildings that are energy efficient and can operate independently of the grid are more resilient to power outages and energy price fluctuations.
- *Health and Comfort*: Indoor environmental quality in buildings is a major determinat of occupant health, comfort, and productivity and is dependent on energy and climate characteristics such as temperature, humidity, and ventilation.
- *Regulation and Policy*: Governments around the world are implementing stricter regulations on building energy use and emissions to meet climate change targets. The ability to monitor and optimize energy and climatic efficiency is key.
- *Urbanization*: Population growth is accompanied by controlled or uncontrolled urbanization, which means that the demand for buildings increases and so does the environmental impact.

A *building digital twin* can play a crucial role in managing the energy and climate characteristics of a building and, more generally, in the context of smart cities [Fuller et al. 2020], towards the goal of resilient, sustainable building design and operation. For example, it can monitor health and comfort characteristics in real time, identify energy inefficiencies, automatically adjust HVAC settings, or optimize building usage patterns. DTs can also use machine learning algorithms to predict future energy needs based on historical data and predict weather conditions. In addition, DTs can be used to simulate and compare different energy-saving measures. For example, if a building manager is considering installing solar panels, a DT could estimate the expected energy production, cost savings, and reduction in greenhouse gas emissions.

1.2 Digital Twin Sensor Infrastructure

In our approach, we assume that there is a network of sensors that forms the underlying specific infrastructure required for energy- and climate-oriented DTs per building. In general, sensors (including actuators and other IoT devices) are used to measure and control aspects such as temperature, humidity, air quality, power and water consumption, lighting, and motion.

The resulting *heterogeneous collection of sensors* generate, process, and transmit time-series data, generally at high frequency, e.g., near real time or real time. The huge amount of data in operational use poses processing, analysis and storage challenges, requiring the use of specialized compression, filtering and databases, as well as real-time processing algorithms and advanced data analysis techniques such as machine learning and data mining.

Together with a hierarchical model of the corresponding building and due to the well-defined time coordinate and georeferences of each sensor data item, a *spatio-temporal data space* is created, which is managed and used by the DT.

1.3 Digital Twin Pilot Project

In 2022, a pilot project was launched by the Andalusian Agency of Education, an agency of the Andalusian government, through a collaboration agreement with the Andalusian University Institute of Domotic and Energy Efficiency (UIDEE), part of the University of Málaga, Spain.

A first version of the building DT system is being implemented in about 430 schools, which will later reach all 5,400 schools. For each school, sensors for, e.g., temperature, CO_2, humidity and energy consumption will be installed, which together with the installation of photovoltaic panels and an adiabatic or evaporative air conditioning system, will be the key to control these variables in order to reduce the energy consumption of schools and educational centers and ensure healthy conditions for users.

1.4 Structure

The article is organized as follows: Section 2 presents related work. Section 3 discusses challenges and requirements. Section 4 introduces climate and energy sensor data. Section 5 outlines a concept for the transmission, preprocessing, and storage of sensor data collected from building sites. Section 6 outlines the visual analytics approach. The last section gives conclusions and outlines future work.

2 RELATED WORK

A *digital twin* [Javaid et al. 2023] is a general concept that refers to a virtual representation or replica of a physical object, system, or process that maps its physical and functional characteristics, behavior, and dynamics, i.e., connects the physical world with the digital one, preferably in real time . An overview of definitions and characteristics of DTs is given in [Barricelli et al. 2019]. As a conceptual and technical framework and computational model, DTs integrate real-time data, sensory inputs, and contextual information to simulate, monitor, analyze, and optimize the physical entity throughout its lifecycle. DTs are key to Industry 4.0 [Sjarov et al. 2020] together with visual computing and VR/AR/XR technologies [Posada et al. 2015]. DTs enable a bi-directional flow of information between the physical and virtual domains, facilitating decision making, predictive analysis, and performance optimization; Jones et al. [Jones et al. 2020] review the state of the art in DT mechanics and characteristics in detail.

DTs for the built environment have been emerging for decades, particularly through building information models (BIM) and in the context of smart cities [Mylonas et al. 2021]. Together with advances in the Internet of Things (IoT) and sensor, actuator, and controller technology [Rivera et al. 2020], DTs for buildings are becoming an integral part of their entire life cycle [Deng et al. 2021].

In the Architecture, Engineering, Construction and Operation (AECO) industry, climate and energy issues are crucial: ”Energy consumption has dramatically increased in buildings over the past decade due to population growth, more time spent indoors, increased demand for building functions and indoor environmental quality, and global climate change. Building energy use currently accounts for over 40% of total primary energy consumption in the U.S. and E.U.” [Cao et al. 2016]. To improve energy efficiency and occupant comfort in public and commercial buildings, Clausen et al. [Clausen et al. 2021] demonstrate how DTs can control heating and ventilation switching from rule-based control to model predictive control. Given a 3D model of a building, e.g., based on CityGML, a general energy assessment can be derived [Giovannini et al. 2014], e.g., used for plausibility and estimation purposes. Billanes et al. [Billanes et al. 2017] detail and discuss the social, technical, and business needs based on various hypotheses related to building managers and occupants regarding energy and climate aspects, such as indoor comfort, electricity costs, business profits, security and privacy: ”The advancement of building intelligence is concerned with plugged-in devices as well as various building instrumentation devices - including sensors, actuators, and controllers - that enable energy-efficient building automation while ensuring the comfort of building occupants.”

Regulatory issues also play a role such as the Energy Performance of Buildings Directive (EPBD), which aims for a highly energy efficient and decarbonized building stock and near zero energy buildings by 2050. Spudys et al.[Spudys et al. 2023] demonstrate how DTs can be applied to "the operational energy assessment of buildings, highlighting the significance of adapting the energy assessment of buildings to state-of-the-art practices for digital assessment, such as smart sensors, real-time measurements, IoT, and digital twins." In this paper, we outline a lightweight, scalable technical approach for an operational system that extracts an operational energy and climate-oriented rating.

To build and operate a sensor network in a building, wireless approaches are becoming increasingly important, especially as a kind of ecosystem for IoT. For example, based on a cross-layer design of lightweight and scalable web services, an infrastructure for wireless sensors can be built and network complexity can be reduced [Sheng et al. 2015]. For a review of the state of the art in energy-efficient data aggregation techniques that extend the life of battery-powered devices and when the number of communication devices is large, see Gulati et al. [Gulati et al. 2022]. For point-to-point transmission, these networks generally suffer from limited bandwidth, power, and resources. Therefore, in our approach, the transmission and reception of sensor data is done through ports. To enable the exchange of data between devices, different protocols based on the 802.11 standard can be used to standardize and structure the communication (such as Wifi, ZigBee, LoRa, ModBus TCP/IP, etc.), each with its own technological characteristics adapted to the different variants.

3 REQUIREMENTS AND CHALLENGES

Implementing and operating a DT for buildings based on a heterogeneous sensor network focused on climate and energy faces a number of common challenges:

- *Data Collection and Integration*: Different types of sensors produce different types of data, often in incompatible formats. In particular, time-series data must be fused and integrated into a consistent, coherent spatio-temporal data space.
- *Real-Time Data Processing and Analysis*: For a system to react and respond intelligently to internal, external, and environmental states and changes, it must process sensor data in real time or near real time.
- *Interoperability*: Heterogeneous sensors and existing home automation or domotics systems must be integrated, and interoperability of all different components must be ensured.
- *Network Connectivity*: Sensors and devices need to communicate over a reliable network. Since there may be areas of weak signals in buildings, sensors must always be connected to the network, and high network traffic and congestion issues must be addressed.
- *Scalability*: As more devices and sensors are added to the system, it must be able to scale more smoothly; as more buildings are included in a DT ecosystem, storage and processing power become more important.
- *Energy Efficiency*: Since one of the main motivations for smart buildings is to save energy, a challenge is to ensure that the network of sensors and devices itself does not consume too much energy.
- *Sensor Accuracy and Reliability*: The quality of data provided by sensors is critical for the efficient operation of the DT. Poor quality or faulty sensors can lead to inaccurate data.
- *Simulation and Modeling Challenges*: To create a DT that accurately reflects the condition of the building, complex models and simulations must be created that can predict how the building will respond to various conditions based on sensor data.
- *Cost and ROI*: Financial aspects are important for development and maintenance costs, and return on investment (ROI) should be clarified.
- *Security and Privacy*: With many IoT sensors and devices, the building becomes more vulnerable to cyber-attacks. Ensuring the security of the smart building’s network and data is critical; user behavior data can also be sensitive due to privacy concerns.
- *Regulation and Standards*: IoT and DTs in smart buildings are increasingly subject to legal regulation, requiring compliance with relevant local, national and international regulations and standards.

In our pilot project, the initial focus is on the technical design, implementation and operation of the sensor networks necessary for the construction of the DT.

4 CLIMATE AND ENERGY SENSORS DATA

In our approach, we have designed and assembled devices that combine a number of different sensors and that are installed in the building, e.g., in the classrooms. Fig. 2 shows an example of a sensor device.

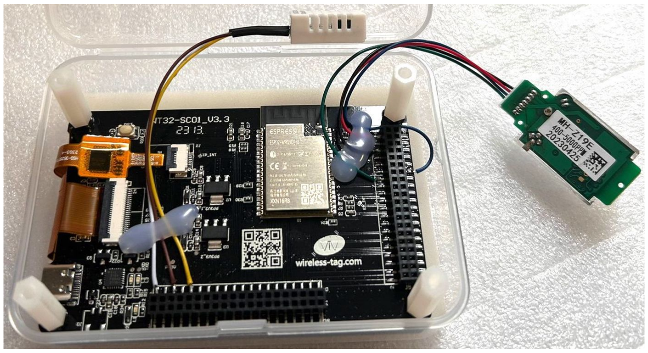

Figure 2: Example of a compound sensor device built for the pilot project.

4.1 Sensor Types for Climate and Energy Data

The following sensors were used in the sensor network for the pilot project:

- *Temperature sensors*, both indoor and outdoor, allow us to respond quickly and accurately to air conditioning (heating or cooling) and optimize energy consumption [Shinoda et al. 2021];
- *Humidity sensors* ensure a healthy environment and help reduce energy consumption, as high humidity can increase this consumption [Xianzhe 2011];
- *Air quality sensors*, e.g., carbon dioxide (CO_2) or volatile organic compounds (VOC), ensure a healthy environment and detect the need to ventilate and, in the best case, program this process when energy costs are lower [Sung and Hsiao 2021];
- *Energy sensors* provide real-time measurements of energy consumption and allow us to manage energy demand, detecting both anomalies and different consumption patterns, thus optimizing energy efficiency [Bae et al. 2021];
- *Light sensors* provide information about the amount of natural light in a room so that artificial lighting can be adjusted to the minimum necessary and unnecessary energy consumption can be avoided [Wagiman et al. 2020];
- *Motion sensors*, for example, detect the presence of people in a room so that other aspects mentioned above, such as lighting and air conditioning, can be managed accordingly [Pedersen et al. 2017].

4.2 Sensor Design and Implementation

The operational use of DTs in buildings requires both a robust and reliable sensor design; in particular, the sensor network installed on site should not imply further complexity induced by, e.g., domotic platforms. To this end, we decided to design and assemble the platform based on the Espressif microchip ESP32-WROVER-B, a generic Wi-Fi and Bluetooth micro controler unit targeting low-power sensor networks. It is integrated into the AMSTRON WT32-SC01 capacitive multi-touch screen, which is equipped with a graphical user interface (GUI) and can be programmed via the PlatformIO user interface. For indoor building units, a compact unit and display, commercially called "Quarth Meter" (Fig. 3), has been designed by UIDEE and provided by IDG2007 as an easy-to-understand communication interface for typical building users.

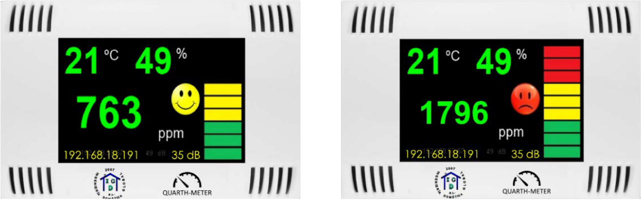

Figure 3: A compact unit for air control as installed in the interior of building units, called "Quarth Meter".

Fig. 4 illustrates the network architecture in terms of how data is collected and stored in the pilot project. EDS concentrators manufactured by Circutor were used to read and store sensor data. These devices also use the ModBus protocol to perform and send the cyclic reading of the photovoltaic energy production parameters and the general or selective consumption of the buildings.

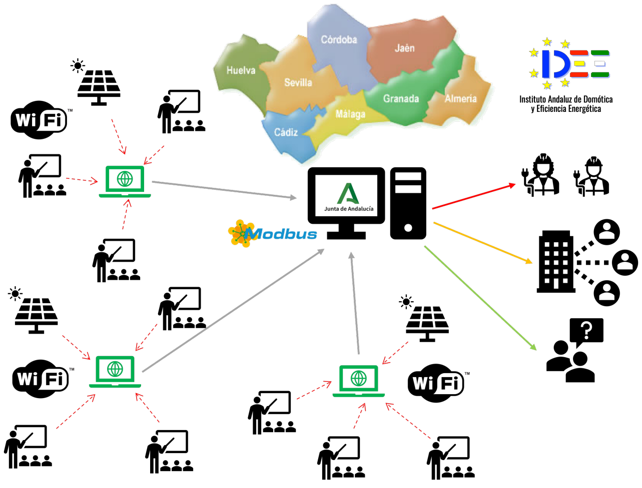

Figure 4: General architecture of for data capturing and storage.

To generate data on air quality and weather conditions, a cyclic reading system of sensors (i.e., temperature degrees, humidity percentage and parts per million of CO_2) located in each classroom has been programmed to send its results via WiFi. In the case of the general energy parameters, they are sent directly to the local information concentrators. The pseudo code is shown below:

```
Definition of basic parameters
setup() block
  Screen activation;
  Reading or modifying WiFi network data;
loop() block
  Connection to the data concentrator;
  Reading values from sensors;
  Display of data on the screen;
  Writing data via ModBus;
```

This data is sent with every two minutes from each of the classrooms and educational centers in the region of Andalusia (Fig. 5). All this information arrives at the central server of the government platform, generating an annual storage of approximately 8TB.

From here, when the system exceeds 50% of its storage capacity, data compression is performed. After that, when it approaches 75% of that capacity, it starts deleting the oldest data to free up space.

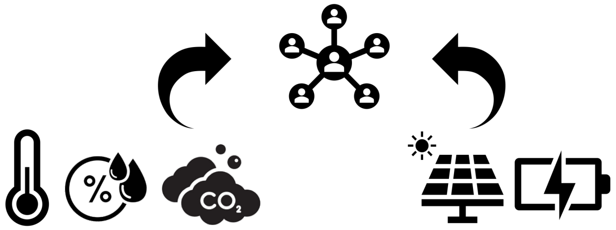

Figure 5: Overview: Real-time data capturing of energy-related data for buildings.

The management of massive time-series data is based on a web platform. It can be accessed by different stakeholders, including the general public, where the accumulated local and global data are presented, and a visualization procedure allows users to access the DT [Merino et al. 2015].

5 TRANSMISSION, PROCESSING, AND STORAGE OF SENSOR DATA

The volume of data to be processed requires a high degree of versatility in its management. Common database approaches for building DTs include:

- **Relational databases** such as MySQL, PostgreSQL, or Microsoft SQL Server, can be used to store sensor data providing structured storage, which allows for efficient querying and indexing of the data.
- **Time-series databases** are designed to handle time-stamped data, making them well suited for sensor data storage (e.g.,. InfluxDB, Prometheus, and TimescaleDB) providing high write throughput and efficient querying based on time ranges.
- **NoSQL databases** (e.g., MongoDB, Cassandra, Apache HBase) offer flexible schema designs and horizontal scalability, efficiently handle large volumes of unstructured or semi-structured sensor data, and provide high write throughput, fault tolerance, and the ability to distribute data across multiple nodes in a cluster.
- **Data lakes**: Data lakes such as Apache Hadoop or Amazon S3, provide a centralized storage repository for storing large volumes of raw sensor data in its original format. Data lakes provide scalable and cost-effective storage and support various data processing and analytics frameworks.
- **Distributed file systems** (e.g., HDFS, GlusterFS) distribute data across a cluster of servers, provide high scalability and fault tolerance and are capable of handling large volumes of data.
- **Cloud storage services** (e.g., Amazon S3, Google Cloud Storage) provide highly scalable and durable storage for sensor data, offering easy scaling storage capacity based on demand and providing built-in data redundancy and disaster recovery capabilities.
- **Edge storage**: Storing sensor data close to the sensors themselves reduces network bandwidth requirements and provides faster access to data for real-time processing and local decision making.

We identified the need for both relational (e.g., MySQL, PostgresSQL) and non-relational databases (e.g.., MongoDB, Cassandra). Due to the massive amount of data and its real-time delivery as well as the different types of query, the dual approach to data management allows for faster, more selective and more accurate searches.

In particular, SQL is used when there are similar relationships between different pieces of data. For example, the names of schools are related to the school's IP in different tables.

The use of NoSQL is limited to massive data that does not require relationships, but rather an established structure that allows its particular query. It manages, in a sense, a kind of ”data lake” [Khine and Wang 2018] and copes with the structured, semi-structured, and unstructured data coming from the sensor networks.

For the pilot project, we evaluated different approaches for data collection. In particular, we have considered the priority of performing minimally invasive efforts that do not require the installation of new wiring. For this reason, we chose to use wireless technologies for communication between sensors within a sensor network on a site.

In order to work with open protocols and to maximize the number of devices that can be placed on the networks, we have chosen Modbus technology and, within it, the Ethernet-based option (TCP/IP). When we talk about ModBus (Modicon Bus), we are not referring to a control system, but to a communication protocol. It was developed in 1973 by the American company MoDiCon (Modular Digital Controller, acquired by Schneider Electric in 1979), by the engineer Dick Morley, for communication between programmable logic controllers (PLCs); being open and public, relatively easy to implement and flexible, it became one of the most popular communication protocols in automation and control systems.

This protocol is the main exponent of BUS-type systems and specifies the procedure used by the controller and slave to exchange data, the format of that data, and how errors are handled. It is the most widely used protocol, especially for its use in energy management, because it is only necessary to know the ModBus map of the device to be used in order to establish communication between master and slave (Fig. 6).

It is used in systems such as ADAM (Advantech), NuDAM (National), ICP, etc. Depending on its design, each device can act as a master, slave, or master/slave. ModBus always operates in master-slave mode (client-server in TCP), as defined by the manufacturer, in pairs, with the master (client) always controlling communication with the slaves (servers). These are limited to returning the requested data or performing the action specified by the master. Each slave has an assigned address and devices with the same address cannot coexist. The master not only collects information from the slaves through queries, but can interact with them or change their state, being able to read and write information in any of them. A device must initiate a request and then wait for a response. Typically, the master is a SCADA (Supervisory Control And Data Acquisition) system.

Practically, due to the construction of the protocol and despite the fact that they can be numbered (as mentioned above) between 1 and 255, no more than 32 slaves can be connected on the same line. If we want to connect a larger number of devices, it is necessary to use different lines and, in order to have communication between them, to connect them to gateways that convert RTU to TCP/IP and, once in TCP, they communicate between them using, for this purpose, the IP that has been assigned in that network layer. In ModBus TCP/IP networks, there can be more devices in the network (as many as Ethernet supports) and also the transfer speed is higher, 10/100 Mbaud. The transmission of information is not limited to one type of data, which allows a certain flexibility in the exchange of data. If a 16-bit data is transmitted, its representation is not subject to any restriction, so it can be a signed word data, a 16-bit unsigned integer or the upper part of a 32-bit float representation, etc. The representation of the value is defined by the specification given by the manufacturer of the device, which allows the representation of a wide range of values. It is up to the master to understand how the slave stores information in memory and decode it correctly. It is recommended that the documentation reflect the word order used by the system. Byte order can also be added as a system configuration option with basic encoding and decoding functions if this flexibility in implementation is required. Because the packet size is limited to 253 bytes, devices are limited in the amount of data that can be transferred. The most common function codes can transfer between 240 and 250 bytes of data from the slave data model, depending on the code.

ModBus TCP is a variant of the Modbus communication protocol that allows physical input/output devices to communicate over an Ethernet network. Specifically, the protocol defines the use of ModBus messages in an Intranet or Internet environment using TCP/IP protocols. It is easy to implement for any device that supports TCP/IP sockets. All requests are sent over TCP using the registered port 502 and typically use half-duplex communication over a given connection. This means that there is no advantage to sending additional requests over a single connection while a response is pending. In addition, it allows for real-time data transfer, which is essential for applications that require fast and reliable communication, such as industrial control and monitoring. In our case, the data transferred via this technology is also sent via TCP, to a Synology server in charge of storing it, using the appropriate security protocols. The information from the air quality sensors is collected at two-minute intervals and the photovoltaic energy data is collected at 15-minute intervals, which is sufficient given the nature of the data to be processed, and the set of data received is sent to the server every 15 minutes (so as not to saturate the communication). Finally, for each data extraction request, graphs and charts are generated and stored in folders on the internal server, displayed in the visualization and updated every 15 minutes.

6 ANALYTICS FOR BUILDING DIGITAL TWINS

In our pilot project, we are addressing the following first, concrete analytical features of the system with respect to energy and climate issues:

- *Room Scheduling*: Improving the scheduling and the allocation and use of rooms based on energy and climatic characteristics. The knowledge of the climatic and energy parameters of the different rooms of the building allows us to the planning of the rooms and to modify the habits of use of the same in order to achieve a better use of them and a lower energy consumption.
- *Occupancy-based services*: By analyzing parameters such as CO_2 concentration, we can simultaneously estimate the number of users. By analyzing occupancy data, the system can implement services such as demand-responsive ventilation and adaptive lighting, thereby saving energy and improving comfort when the rooms are occupied and saving energy when they are not.
- *Energy cost savings*: In contrast to the rigid rules and procedures for air conditioning, heating, and cooling in public buildings, we can use the data from the DT to create room-specific climate and energy plans to optimize the energy balance and save money. Energy efficiency, predictive maintenance, and improved building utilization can reduce operating costs.
- *Climatic and energy-sensitive room usage*: The analysis of data such as the photovoltaic (self-)energy production or the outdoor temperature facilitates the energy optimization with respect to the working conditions in the building. In particular, the use of rooms can be adapted to the measured or predicted conditions, e.g. ventilation of rooms by air conditioning with outside air at the desired temperature, adaptation of use times to the electricity production of the building, etc.
- *Monitoring energy efficiency*: By monitoring energy usage patterns in real time, the system can identify inefficiencies and suggest changes to reduce energy waste, such as adjusting temperature settings, controlling lighting based on natural daylight availability or occupancy, etc (Fig. 7).
- *Optimal learning environments*: By continuously monitoring and adjusting CO_2 levels, lighting, temperature, and humidity, the DT can help create an optimal learning environment for students, improving their concentration, health, cognitive performance, and productivity.

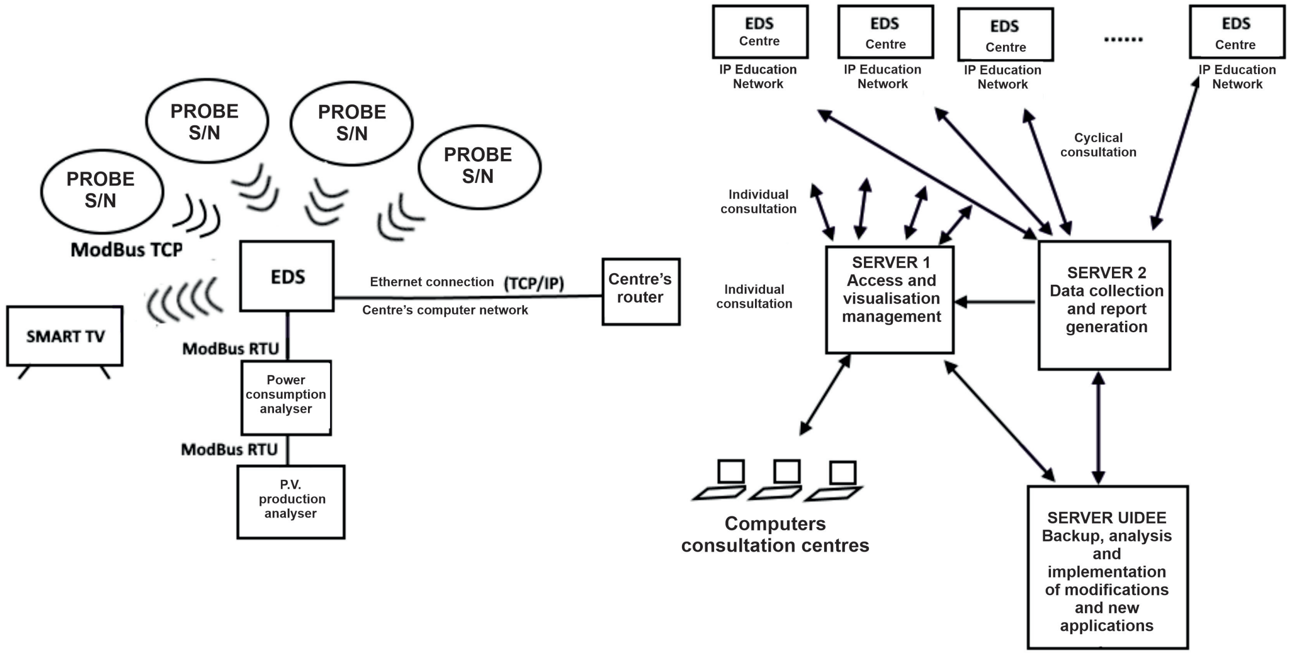

Figure 6: Protocols used in our pilot DT project.

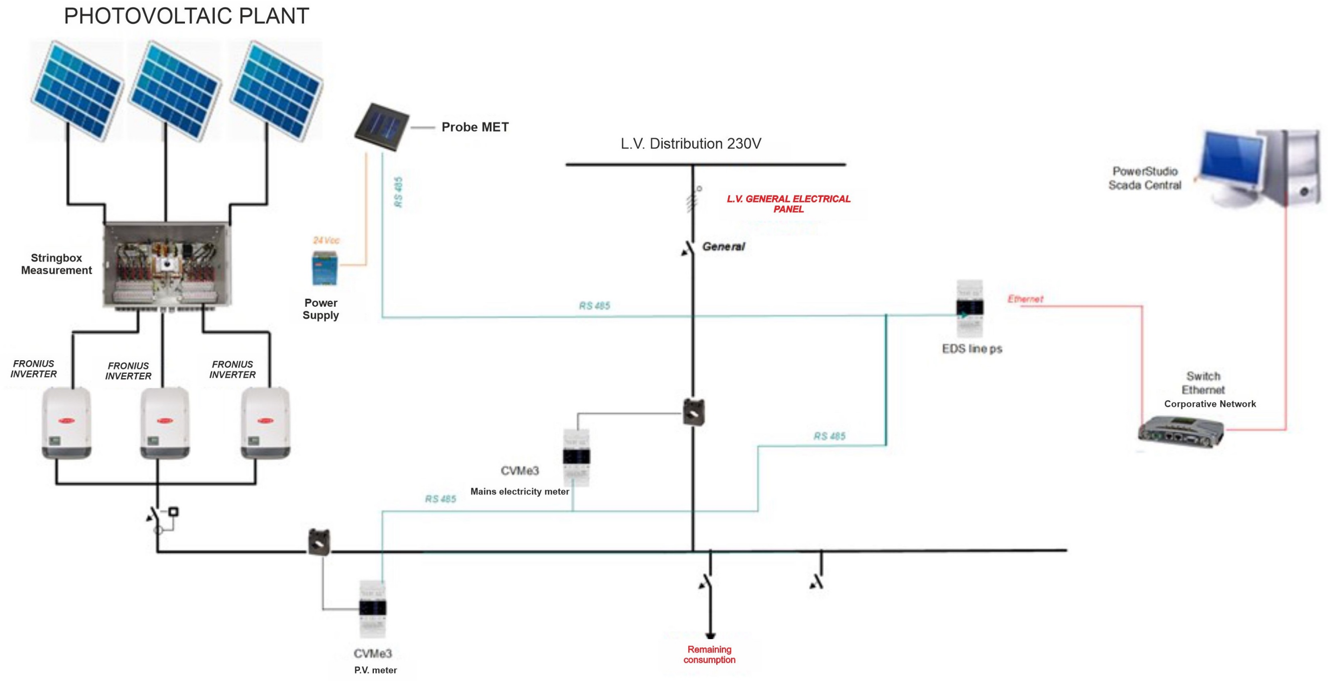

Figure 7: Monitoring of energy production and consumption

- *Trend prediction*: Over time, the system can help understand how the building’s performance is changing and predict future trends, such as increasing or decreasing energy consumption, air quality levels, etc.
- *Green building certifications*: The data collected and the improvements made can help achieve green building certifications such as LEED or BREEAM, which can enhance the school’s reputation and contribute to sustainability goals. In particular, climate and energy-oriented DTs for buildings provide the basis for Energy Performance Certification (EPC) as a core element of the EU’s energy efficiency policy for buildings.

7 CONCLUSIONS AND FUTURE WORK

In our pilot project, we are focusing on energy and climate aspects of DTs for public buildings. To this end, we have so far installed a sensor infrastructure in 430 educational centers and schools. Our first studies are based on the following collected data:

- Energy consumption of the buildings from conventional energy.
- Energy produced by the solar panels installed in each of them.
- Temperature in each of the classrooms.
- Humidity level in each of the classrooms.
- Percentage of CO_2 measured in the air.

From a technical perspective, the deployment and operation of the heterogeneous sensor networks could be implemented based on low-cost, robust devices assembled for this project based on standard IoT and sensor hardware components. We also decided to use only wireless connections within the buildings to simplify and speed up the installation processes.

In the case of buildings, on the one hand, there is a public need for action due to increasing demands on resilience and energy consumption caused by climate change. On the other hand, the use of buildings must provide the highest possible quality for living, health and working. The DT pilot project allows us to combine these two aspects in one technical solution.

Although we are at a very early stage in our pilot project, we are already seeing the first applications: (a) improving resilience, i.e., increasing the ability to adapt quickly and safely to any circumstance, whether or not it has happened in the past; (b) improving efficiency, i.e., ensuring that decisions are made taking into account the impact they may have on the various processes taking place in the system; (c) citizen-oriented management, i.e., as advocated by the EU’s 2030 Digital Decade, the DTs must involve citizens to inform them with information and adapt the management of systems to their needs; (d) contribution to sustainability, i.e., there is a clear commitment to the new concept of sustainable cities; the aim is to adapt to climate change through planning, optimal management of infrastructures and citizen participation.

In particular, one future research direction is autonomous building control that anticipates and adapts itself to user needs in near real time, so that physical conditions adapt to current and expected user behavior, taking into account, for example, room occupancy, type of activity, lighting needs, or weather forecasts. In the long-term, these are key DT capabilities for creating ”conscious and cognitive buildings”.

ACKNOWLEDGMENTS

This work was partially supported by the University of Málaga and CBUA. This work was also partially funded by the Federal Ministry of Education and Research, Germany through grant "TreeDigitalTwins" (033L305) and grant "AI research group FFS-AI" (01IS22062).

REFERENCES

Ayesha Asif and Muhammad Zeeshan. 2020. Indoor temperature, relative humidity and CO2 monitoring and air exchange rates simulation utilizing system dynamics tools for naturally ventilated classrooms. *Building and Environment* 180 (2020), 106980. https://doi.org/10.1016/j.buildenv.2020.106980

Yeonjin Bae, Saptarshi Bhattacharya, Borui Cui, Seungjae Lee, Yanfei Li, Liang Zhang, Piljae Im, Veronica Adetola, Draguna Vrabie, Matt Leach, and Teja Kuruganti. 2021. Sensor impacts on building and HVAC controls: A critical review for building energy performance. *Advances in Applied Energy* 4 (2021), 100068. https://doi.org/10.1016/j.adapen.2021.100068

Barbara Rita Barricelli, Elena Casiraghi, and Daniela Fogli. 2019. A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. *IEEE Access* 7 (2019), 167653–167671. https://doi.org/10.1109/ACCESS.2019.2953499

Joy Billanes, Zheng Ma, and Bo Jørgensen. 2017. Consumer Central Energy Flexibility in Office Buildings. *Journal of Energy and Power Engineering* 11 (10 2017). https://doi.org/10.17265/1934-8975/2017.10.001

Xiaodong Cao, Xilei Dai, and Junjie Liu. 2016. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy and Buildings* 128 (2016), 198–213. https://doi.org/10.1016/j.enbuild.2016.06.089

Anders Clausen, Krzysztof Arendt, Aslak Johansen, Fisayo Sangogboye, Mikkel Kjærgaard, Christian Veje, and Bo Jørgensen. 2021. A digital twin framework for improving energy efficiency and occupant comfort in public and commercial buildings. *Energy Informatics* 4 (09 2021), 40. https://doi.org/10.1186/s42162-021-00153-9

Min Deng, Carol Menassa, and Vineet Kamat. 2021. From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction* 26 (02 2021), 58–83. https://doi.org/10.36680/j.itcon.2021.005

Aidan Fuller, Zhong Fan, Charles Day, and Chris Barlow. 2020. Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access* PP (2020), 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

Luca Giovannini, Stefano Pezzi, Umberto Di Staso, Federico Prandi, and Raffaele de Amicis. 2014. Large-Scale Assessment and Visualization of the Energy Performance of Buildings with Ecomaps - Project SUNSHINE: Smart Urban Services for Higher Energy Efficiency. In *Proceedings of the 3rd International Conference on Data Management Technologies and Applications* (Vienna, Austria), Markus Helfert, Andreas Holzinger, Orlando Belo, and Chiara Francalanci (Eds.). SciTePress, 170–177. https://doi.org/10.5220/0004997001700177

Kamal Gulati, Raja Sarath Kumar Boddu, Dhiraj Kapila, Sunil L. Bangare, Neeraj Chandnani, and G. Saravanan. 2022. A review paper on wireless sensor network techniques in Internet of Things (IoT). *Materials Today: Proceedings* 51 (2022), 161–165. https://doi.org/10.1016/j.matpr.2021.05.067 CMAE’21.

Fatma S. Hafez, Bahaaeddin Sa’di, Safa Gamal, Yun Taufiq-Yap, Moath Alrifaey, Mehdi Seyedmahmoudian, Alex Stojcevski, B. Horan, and Saad Mekhilef. 2023. Energy Efficiency in Sustainable Buildings: A Systematic Review with Taxonomy, Challenges, Motivations, Methodological Aspects, Recommendations, and Pathways for Future Research. *Energy Strategy Reviews* 45 (01 2023), 101013. https://doi.org/10.1016/j.esr.2022.101013

Mohd Javaid, Abid Haleem, and Rajiv Suman. 2023. Digital Twin applications toward Industry 4.0: A Review. *Cognitive Robotics* 3 (2023), 71–92. https://doi.org/10.1016/j.cogr.2023.04.003

David Jones, Chris Snider, Aydin Nassehi, Jason Yon, and Ben Hicks. 2020. Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology* 29 (2020), 36–52. https://doi.org/10.1016/j.cirpj.2020.02.00

Pwint Khine and Zhao Wang. 2018. Data lake: a new ideology in big data era. In *Proceedings of the 4th Annual International Conference on Wireless Communication and Sensor Network* (Wuhan, China) *(ITM Web of Conferences, Vol. 17)*. EDP Sciences, 03025. https://doi.org/10.1051/itmconf/20181703025

Salvador Merino, Javier Martínez, and Francisco Guzmán. 2015. Metadomotic optimization using genetic algorithms. *Appl. Math. Comput.* 267 (2015), 170–178. https://doi.org/10.1016/j.amc.2015.04.029 The Fourth European Seminar on Computing (ESCO 2014).

Georgios Mylonas, Athanasios Kalogeras, Georgios Kalogeras, Christos Anagnostopoulos, Christos Alexakos, and Luis Muñoz. 2021. Digital Twins From Smart Manufacturing to Smart Cities: A Survey. *IEEE Access* 9 (2021), 143222–143249. https://doi.org/10.1109/ACCESS.2021.3120843

Theis Heidmann Pedersen, Kasper Ubbe Nielsen, and Steffen Petersen. 2017. Method for room occupancy detection based on trajectory of indoor climate sensor data. *Building and Environment* 115 (2017), 147–156. https://doi.org/10.1016/j.buildenv.2017.01.023

Jorge Posada, Carlos Toro, Iñigo Barandiaran, David Oyarzun, Didier Stricker, Raffaele de Amicis, Eduardo B. Pinto, Peter Eisert, Jürgen Döllner, and Ivan Vallarino. 2015. Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet. *IEEE Computer Graphics and Applications* 35, 2 (2015), 26–40. https://doi.org/10.1109/MCG.2015.45

Luis F. Rivera, Hausi A. Müller, Norha M. Villegas, Gabriel Tamura, and Miguel Jiménez. 2020. On the Engineering of IoT-Intensive Digital Twin Software Systems. In *Proceedings of the IEEE/ACM 42nd International Conference on Software Engineering Workshops* (Seoul, Republic of Korea). ACM, New York, USA, 631–638. https://doi.org/10.1145/3387940.3392195

Zhengguo Sheng, Chinmaya Mahapatra, Chunsheng Zhu, and Victor C. M. Leung. 2015. Recent Advances in Industrial Wireless Sensor Networks Toward Efficient Management in IoT. *IEEE Access* 3 (2015), 622–637. https://doi.org/10.1109/ACCESS.2015.2435000

Jun Shinoda, Angelos Mylonas, Ongun Kazanci B., Shin-ichi Tanabe, and Olesen Bjarne W. 2021. Differences in temperature measurement by commercial room temperature sensors: Effects of room cooling system, loads, sensor type and position. *Energy and Buildings* 231 (2021), 110630. https://doi.org/10.1016/j.enbuild.2020.110630

Martin Sjarov, Tobias Lechler, Jonathan Fuchs, Matthias Brossog, Andreas Selmaier, Florian Faltus, Toni Donhauser, and Jörg Franke. 2020. The Digital Twin Concept in Industry – A Review and Systematization. In *Proceedings of the 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation* (Vienna, Austria). IEEE, 1789–1796. https://doi.org/10.1109/ETFA46521.2020.9212089

Paulius Spudys, Nicholas Afxentiou, Phoebe-Zoe Georgali, Eglė Klumbytė, Andrius Jurelionis, and Paris Fokaides. 2023. Classifying the operational energy performance of buildings with the use of digital twins. *Energy and Buildings* 290 (04 2023), 113106. https://doi.org/10.1016/j.enbuild.2023.113106

Wen-Tsai Sung and Sung-Jung Hsiao. 2021. Building an indoor air quality monitoring system based on the architecture of the Internet of Things. *EURASIP Journal on Wireless Communications and Networking* 2021, 1, Article 153 (2021), 41 pages. https://doi.org/10.1186/s13638-021-02030-1

Khairul Rijal Wagiman, Mohd Noor Abdullah, Mohammad Yusri Hassan, and Nur Hanis Mohammad Radzi. 2020. A new optimal light sensor placement method of an indoor lighting control system for improving energy performance and visual comfort. *Journal of Building Engineering* 30 (2020), 101295. https://doi.org/10.1016/j.jobe.2020.101295

Nengmou Wang and Hojjat Adeli. 2014. Sustainable building design. *Journal of Civil Engineering and Management* 20, 1 (2014), 1–10. https://doi.org/10.3846/13923730.2013.871330

Hua Xianzhe. 2011. Room temperature and humidity monitoring and energy-saving system. In *Proceedings of the 6th International Conference on Computer Science & Education (ICCSE)* (Singapore). IEEE, 537–540. https://doi.org/10.1109/ICCSE.2011.6028696