A Digital Twin Architecture for Smart Buildings

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Abstract—**Smart buildings aim to increase energy performance while maintaining or improving the indoor living conditions. A digital twin of a smart building should be able to provide a virtual representation of the actual building behavior in real-time through accurate simulations considering both the air quality and energy related performance. Such digital twin setups are useful for investigating the building behavior in a non-invasive manner and for validating the effectiveness of novel management and control algorithms under realistic conditions before their actual deployment in real buildings. This paper presents the key functional requirements that a digital twin platform for building should satisfy. Then, an architecture is proposed for the development of a digital twin for buildings while design guidelines are also provided. The architecture includes a software platform for the integration of smart algorithms and user interfaces to enable the intelligent operation of buildings. The digital twin captures the indoor environmental conditions by modeling the operation of the Heating, Ventilation and Air-Conditioning (HVAC) system, the occupants' behavior, the building's thermal insulation, and the outdoor weather conditions. At the same time, the building electricity consumption is characterized by modelling the load consumption according to users' habits, the HVAC operation, the renewable energy generation, and the weather conditions. An example for the development, validation, and calibration of a digital twin of an actual building is demonstrated in this paper. Furthermore, some use cases are demonstrated through the software platform to investigate how an operational fault or an actual battery system, connected in a hardware in the loop configuration, can affect the indoor environmental conditions and the energy performance of the building.**

Keywords—**Air quality, buildings, digital twin, energy management, operational faults.**

I. INTRODUCTION

Buildings globally consume a big portion of the total electricity and account for a significant part of Greenhouse Gas (GHG) emissions. Specifically, the building sector represents 30% of the global energy use and around 55% of the total electricity consumption. In addition, buildings are responsible for 28% of energy-related Carbon Dioxide (CO_2) emissions worldwide [1]. On top of this, humans spend most of their time within buildings which makes the Indoor Environmental Quality (IEQ[1]) important, as well as keeping Indoor Air Quality (IAQ) in comfortable levels for occupants. For example, when Volatile Organic Compounds (VOC) in an indoor space exceeds the acceptable concentration of 0-250 parts per billion (ppb) may cause headaches, nose and throat inflammation in short-term, while radical long-term effects are anxiety and respiratory diseases. In addition, if CO_2 exceeds the range of 400-1000 ppm results in drowsiness, headaches, and loss of attention. On the other hand, energy efficiency[2] and intelligent energy management are crucial for achieving climate neutral buildings. Hence, building energy management systems (BEMSs) have been introduced to improve the energy efficiency, automate procedures related to the energy management and demand response, coordinate the generation from distributed and Renewable Energy Sources (RES), and manage indoor environmental conditions [2].

Towards the massive deployment of smart buildings, technologies related to electricity generation and demand coordination, and IEQ management and control, should be integrated together over the Internet of Things (IoT) framework. In this direction, the development of a digital twin for buildings can support the design stage, can improve the building performance evaluation under different operating scenarios, and can facilitate the development of novel solutions, as stated in [3]. According to IBM, a digital twin, is a virtual model designed to accurately reflect a physical object. This virtual model should be executed in real-time, or faster than real-time, and it should consider the representation of all the key domains of a building, including the electricity, air quality, thermal comfort, and users' behavior. Digital twins incorporate field measurements either for calibrating the model to achieve high accuracy or for replicating the exact operating conditions of a building in a virtual environment. The development of such digital twins can enable the evaluation of the building performance and behavior under rare or extreme conditions and in a non-invasive manner that can be used for planning, management and preventing maintenance [4]. In addition, the digital twin can be used for testing, demonstrating and evaluating novel and intelligent monitoring and control solutions in a very realistic environment, considering Hardware In the Loop (HIL) configuration, before applying them in actual buildings.

A great attention is given in the development of digital twins for buildings. In [5], a comparison between a digital twin and a Building Information Modeling (BIM) is provided. The research study in [6] uses the BIM to gain understanding for the geometric and parametric properties of buildings and combines them with data collected by IoT sensors to create a digital twin. In the aforementioned work, the digital twin is used to visualize and monitor the indoor environmental conditions in real-time through an interactive dashboard. In [7], a broad learning system is introduced to improve the accuracy of a building digital twin, focusing mainly on industrial level HVAC system, with the chillers, cooling towers and cooling water pumps. Such digital twins give emphasis on building's thermal comfort can be used for maintenance purposes, where the replica of the actual HVAC equipment is used to solve a maintenance problem, optimize the process, and predict failures [8]. The prior-mentioned approaches provide opportunities for different kind of investigations, for predictive maintenance and decision-making related to the building's indoor comfort. However, the relation of the HVAC processes with the energy performance of the building in terms of electricity consumption and generation is not properly captured.

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[1] IEQ corresponds to IAQ, thermal comfort, lighting and acoustics.

[2] Building's total energy efficiency corresponds to efficiency of the energy consumed and generated by the building.

A holistic framework that emulates the all the key properties of a building (i.e., electricity consumption and generation, heating and cooling of indoor spaces, air quality, etc.) can create new opportunities for introducing the energy sector integration approach at the building level. In this context, a HVAC control considering electricity demand flexibilities [9] or a joint optimization scheme for electric vehicle charging and HVAC operation considering comfort preferences [10] have been proposed, demonstrating that through the energy sector integration concept, a significant reduction of electricity cost can be achieved. Hence, a digital twin should be able to accurately capture the behavior of the building concerning all the important aspects of its operation.

The development of a digital twin requires the modeling of the various building's components and their interconnection. The work presented in [11] facilitates a building energy modeling engine created by the US's department of energy, called *EnergyPlus* [12], to create a digital twin for improving building's energy footprint and asset performance. The *EnergyPlus* model is developed based on Ordinary Differential Equations (ODEs) for each building zone considering the BIM, historical energy, and IoT data for simulating at the same time the indoor temperature, air quality, and the electricity consumption and generation. While in [11] the *EnergyPlus*-based digital twin is used to evaluate the accuracy of data-driven predicting models for estimating building related parameters, the specific simulation software is capable of capturing a holistic building simulation, considering both electricity and indoor living conditions. Alternative simulation tools for building thermal and air quality response may consider the finite element modeling approach for further accuracy, resolution, and granularity [13] compared to ODEs per building zone. Unfortunately, the finite element simulations require intense computational complexity that does not allow the execution of the building digital twin model in real-time.

The main objective of this paper is the development of a software platform and a digital twin to enable holistic performance evaluations and HIL investigations in buildings. First, the functional requirements of a digital twin are clearly defined and then a building digital twin architecture is proposed based on a digital twin model and an associated software platform. The proposed digital twin architecture and its development to replicate the behavior of an actual building are the key contributions of this paper. The proposed building digital twin is a holistic approach to capture all the dimensions of a building, including the thermal, air quality, electricity, and user behavior. The developed digital twin is capable of real-time run or faster than real-time, allowing HIL experiments and investigation of multiple scenarios in a non-invasive manner. In addition, the proposed platform incorporates IoT measurements for calibrating and validating the digital twin's accuracy and provides visualizations and user-friendly interfaces. A key feature of the proposed digital twin, which is particularly useful for research and innovation purposes, is the capability of integrating smart management and control schemes in the loop with the digital twin to examine in real-time their effectiveness in a realistic environment, as demonstrated through selected use cases in this paper.

The rest of the paper is structured as follows. In Section II, the functional requirements are presented, while the proposed architecture for developing a building digital twin is described in Section III. The validation of the digital twin accuracy is presented in Section IV and selected investigations under different conditions are demonstrated in Section V. The paper concludes in Section IV.

II. OBJECTIVES AND FUNCTIONAL REQUIREMENTS

A. Objectives

This work focuses on the development of a building digital twin and a software platform for the *KIOS Smart Buildings Living Lab*, which is a part of the KIOS research infrastructure (kios.ucy.ac.cy/research-infrastructures). The main goal of the digital twin is to create the foundations for research and innovation in the building sector, aiming to improve indoor environmental quality and to enhance building's total energy efficiency. Specifically, the development of the digital twin contributes towards the following objectives. First, to facilitate high-quality, current and future research and innovation needs related to the testing and validation of intelligent algorithms, hardware components, and new technologies associated with the building sector. In addition, to enable the validation, demonstration, and evaluation of research outcomes for monitoring, fault diagnosis, control, optimization, security, and management of the build environment and building's systems. This digital twin aims to promote technology and knowledge transfer to industry and building operators, supporting pilot demonstrations in research and innovation projects associated with buildings.

B. Functional Requirements and Capabilities

The development of a building digital twin framework aims to support research and innovation activities related to the building sector. The key functional requirements and capabilities of the digital twin and its associate software platform are listed below:

- The building digital twin should follow a holistic modeling approach able to capture all the aspects of a building including thermal, air quality, electricity, and user behavior dimensions with at least per building zone granularity, while enabling real time (or faster) execution in a typical computer to enable real-time HIL tests. For this reason, an ODE per zone modeling approach should be followed for the thermal and air quality behavior by considering BIM and weather conditions, while the electrical behavior of the building should be incorporated through a macroscopic power balance approach.
- The software platform should be able to interact with both the actual building and the digital twin for calibration and validation purposes. The interaction with the actual building can be enabled through IoT sensors (e.g., electricity meters, temperature sensors, etc.) and through intelligent appliances (e.g., photovoltaic-battery inverter, HVAC, etc.). On the other hand, the software platform should interact with the digital twin by exchanging measurements and control set-points in every solver step.
- The software platform should support data aggregation and visualization of the building operation considering data related to the operation of both the actual building and the digital twin. The custom-made visualization dashboards should be supported to enable live comparison of different operational variables.
- The software platform should support the creation of multiple *what if* scenarios with different weather conditions, user habits, building configurations,

component failures or degradation and system disturbances for evaluating the building's performance in a non-invasive manner and under different conditions.

- The digital twin should support the real time and in the loop integration of smart modules and devices. Intelligent algorithms related to intelligent monitoring, management, control, optimization, and fault diagnosis of buildings should be integrated as smart modules within the software platform. These smart modules should act as a HIL configuration with the digital twin, and in certain cases, with the actual building appliances as well.
- The digital twin should be used for validating research outcomes in a realistic building setup and for demonstrating innovation activities in a relevant environment to achieve a high technology readiness level. The digital twin model and the related software platform will be provided as an open-source software to be used by internal and external users working in the building sector.

III. ARCHITECTURE FOR THE DIGITAL TWIN FRAMEWORK

The architecture of the proposed digital twin framework is presented in Figure 1. The architecture consists of the physical layer that corresponds to the actual building and its components, the digital twin layer with the holistic building simulation model, and the software platform that interacts with both the digital twin and the actual building for data aggregation, visualization, and intelligent management.

A. Physical Layer

The actual building that is replicated through the digital twin representation is the SFC03 building, located in the campus of the University of Cyprus. As illustrated in Figure 1, SFC03 is a two-level building with gross area of 630 m^2, which is used for office work and laboratories. A Photovoltaic (PV) system of 80 kWp is installed in the surrounding area to partially cover the electrical demand of the building, while a battery storage system (15kW-15kWh) is also installed in the lab and can be used, among other purposes, for enhancing the self-consumption capabilities of the building. The heating and cooling needs are satisfied through a central HVAC system. The users' behavior is incorporated in a stochastic manner according to the user arrival and departure time and the equipment utilization by each user.

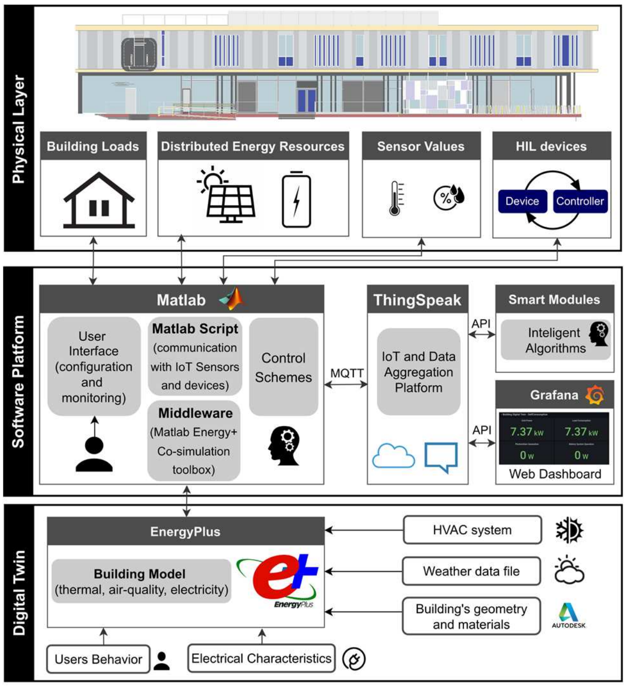

Figure 1: Proposed architecture of the building digital twin framework.

In addition, several sensors have been installed to monitor the building performance. IoT sensors have been installed in the entire building to monitor the IEQ properties (i.e., temperature, humidity, CO2, VOC, PMs) of the building with high granularity. The sensor measurements can be retrieved through Application Programming Interfaces (APIs). Energy related measurements from smart meters and smart PV and battery inverter are retrieved over the Modbus TCP protocol to measure the overall electricity consumption and generation profile of the building. The planimetries and electro-mechanical plans has also been used for designing the 2 and 3 Dimensional (2D and 3D) representation of the building, and for providing the required information for the HVAC system, the electrical loads, and lights of the building.

B. Digital Twin

The first step for the creation of digital twin model is the design of the building's geometry. The lack of an existing BIM model as in [6], required the design of a model from scratch. This was done using the related software from *Autodesk*. The already existing 2D architecture floor level plans of the building in *AutoCAD* were transformed into 3D in *Revit*. The final building's geometry is shown in Figure 2 for the first floor of the selected building. Figure 3 shows the design of a selected room, which will be used in Section IV for validating the energy/thermal model of the building.

The next step for the implementation of the digital twin is the creation of the simulated model in *EnergyPlus*, as shown in Figure 1, that takes as inputs the geometry created and weather data for the specific location. The weather data file (.epw) is acquired from relevant websites providing data from weather stations (e.g., climate.onebuilding.org, weatherapi.com). In *EnergyPlus*, the HVAC system of the building is created using technical documentation of the system and the electromechanical plans. In addition, the electrical behavior of appliances (including the HVAC system), the PV generation, and the operation of the battery storage system is included in the modeling of the building. Certain stochastic profiles are also considered to emulate the user's behavior as well.

C. Software Platform

The physical layer and the digital twin are integrated together through a common software platform that

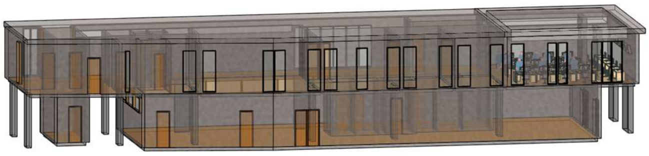

Figure 2: SFC03 building geometry.

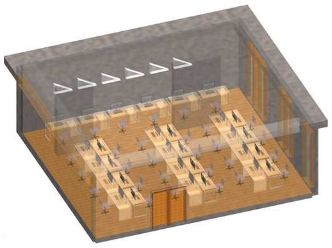

Figure 3: Geometry of a selected room used to validate the thermal behavior.

Figure 4: Grafana Dashboard

communicates with both systems as shown in Figure 1. The interaction between the *EnergyPlus* digital twin model and the software platform is performed through the *Matlab Energy Plus Co-simulation Toolbox*. Considering this toolbox, a desktop application with user interface is developed using the *MATLAB App Designer* which is integrated in the loop with the *EnergyPlus* software. As a result, at each simulation step, *MATLAB middleware* captures the simulated results from *EnergyPlus* and provide input data and control set-points for the next step of the simulation. The simulation timestep can vary from 1 minute to 1 hour according to *EnergyPlus*, which can affect the overall accuracy of the digital twin and the required processing time. It should be noted that the ratio between the simulation time and the actual time can be configure by the *MATLAB middleware*, allowing the building digital twin to run in real time or even faster. A real time execution is needed for HIL investigation while the faster than real time is utilized to evaluate the performance of multiple scenarios that can run, evaluated in real time. Through the user interface of the *MATLAB middleware*, users' behavior patterns, electrical consumption and generation profiles can be configured, based on either selected historical days or live data input. Furthermore, the preferable comfort levels can be adjusted over the day, and specific disturbances or component failures can be emulated to create different potential conditions and scenarios. Finally, intelligent device-level management, control and fault diagnosis schemes can be integrated as smart module within the *MATLAB middleware* to interact with the digital twin in every simulation step.

On the other hand, the interaction between the actual building and the software platform is achieved through another *MATLAB* script (Figure 1) that ensures the communication with IoT sensors and intelligent appliances. This *MATLAB script* is able to receive IEQ measurements from the IoT sensors installed in the building, while energy consumption and generation data (from smart meters and PV inverters) are collected through the Modbus TCP communication protocol. Similarly, the same script is used to send coordination signals to the battery inverter (through Modbus TCP) to regulate the storage system operation.

Data collected from both the actual building and the digital twin are uploaded and stored into *ThingSpeak*, a cloud-based IoT and data aggregation platform, through MQTT protocol, as shown in Figure 1. *ThingSpeak* supports REST API calls (HTTP get requests) for a straightforward way to read measurements and write commands in its database. Through the API calls, a web-interface can be integrated for monitoring the operation of both the actual building and the digital twin, by connecting *ThingSpeak* with *Grafana*, an open-source multi-platform for analytics and interactive visualization. The *Grafana* integration is achieved through the Infinity data source plugin, while an example of the developed dashboard is demonstrated in Figure 4. Moreover, the REST API calls can be utilized to integrate building-level smart modules in HIL configuration enabling the intelligent management and optimization of building virtual or actual operation.

IV. VALIDATION PROCEDURE

After the development of the building digital twin and its associated software platform, as shown in Figure 1, the validation of the digital twin model is required to ensure the realistic replication of the building' operating conditions. In addition, a calibration of the model may be required for achieving high accuracy and to trust the digital twin model when it is used in further research and innovation activities.

The validation procedure demonstrated in this section focuses mainly on the thermal behavior of the building digital twin model and it is achieved by running several on site experiments, in a selected room (the one shown in Figure 3). Since *EnergyPlus* uses a temporal model of the thermal behavior of each zone/room in the building, the digital twin generates a single state (i.e., temperature, humidity, etc.) to represent the thermal operation of each building zone (e.g., room). Since it is observed that there is a non-negligible temperature difference inside the room, multiple IEQ sensors have been allocated in the selected room to estimate the average room temperature. The temperature measurements were collected and processed according to a weighted moving average approach to calculate a single temperature state per zone. Four *Airthings Wave Plus* and six *Aeon Multisensors* have been installed in the room to measure the IEQ, as presented in Figure 5.

Another obstacle for the validation of the building digital twin was the lack of some HVAC information (e.g., water temperature, fan coil speed) that affect the model response. In those cases, a reverse engineering approach is applied to identify some missing parameters according to experimental results. Site measurements have been received with air flow meters to identify the fan coil speed in different modes. It is noted that air flow measurements have been obtained from the six fan coil units located in the specific room for different fan speed levels, determined by the thermostat as 1, 2, 3 or auto, and then the measurements were aggregated to calculate the equivalent fan speed of the HVAC system in the selected room. A maximum air inlet speed of 5.14 m/s is measured for the selected room, and the corresponding parameter has been calibrated in the building digital twin model of *EnergyPlus*.

The validation phase for the thermal behavior is separated in two main experimental phases. The first phase focuses on validating the thermal inertia of the building digital twin. The thermal inertia of the building (according to the building material) refers to the ability of a material to conduct and store heat. For capturing this phase related to the thermal inertia of the building, the temperature set-point should be reduced or the HVAC system should be deactivated and then monitor the temperature decrease according to the building thermal inertia. The second phase is more related to the HVAC operation and the thermal energy transmitted to the room by the heating device. During this phase, HVAC related parameters can be validated and re-calibrated. This phase is capture when the room temperature setpoint is increased.

In the following subsections, two experimental studies are demonstrated to validate the accuracy of the developed building digital twin. In the first experiment, the air mass flow of the fan coil was kept to the maximum, while for the second experiment it was set to auto.

A. Validation experiment with maximum fan coil speed

This experiment was performed on 25/01/2022, the HVAC system was in operation from 08:00, and the windows of the room were closed for the whole duration of the experiment. The weather conditions of the selected day are incorporated in the EnergyPlus model through data obtained from weather sites and the utilization of the room (number of people in the room) is considered as a manual entry to the model. Steady state temperature conditions were ensured before initiating the validation phase at 12:00 with a temperature set-point set to 24ºC. Then, the setpoint was set at 26ºC at 14:00, and at 22.5ºC at 16:00. The temperature received by the four *Airthings Wave Plus* and six *Aeon Multisensors* are presented demonstrated in Figure 6 along with the temperature set-point and the temperature calculated by the building digital twin according to the EnergyPlus calibrated model. During this experiment the fan coil air flow speed is constant and equal to its maximum value until 19:30, where the HVAC system is deactivated, as shown in Figure 7.

It is observed that the calculated temperature by the digital twin (blue line) is very close to the actual temperature of the room (red line), which is calculated as the weighted moving average value from the ten temperature sensor values (grey lines). The accuracy of the digital twin model, when the temperature is increasing, validates the modeling accuracy of the HVAC system (phase 2), while the accuracy when the temperature is decreasing, ensures the accuracy of the building thermal insulation materials (phase 1). Through this experiment, the accurate thermal behavior of the digital twin model is validated when a constant fan coil speed is used.

B. *Validation experiment with automatic fan coil speed*

The second validation experiment is performed on 23/02/2022 and the experiment focused on the thermal behavior of the building when the fan coil speed was set to automatic mode. In this case, the HVAC is activated at 08:00 and the temperature set-point is set to 24.4 ºC. Then, at 12:00 and at 17:15 the set-point is decreased to 23.5 ºC and to 22.8 ºC respectively, while the HVAC is deactivated at 20:00.

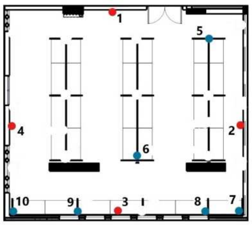

Figure 5: IAQ sensors position (Airthings 1-4, and Aeon 5-10).

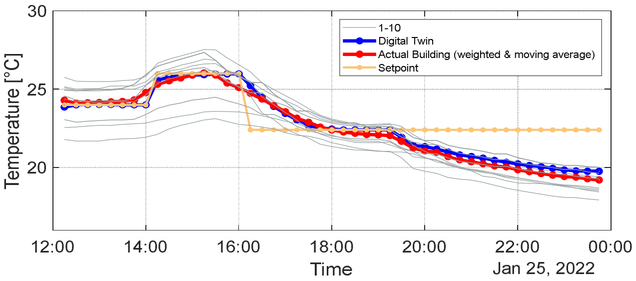

Figure 6: Setpoint and sensors temperture, actual room temperature, and digital twin temperature when fan coil speed is constant.

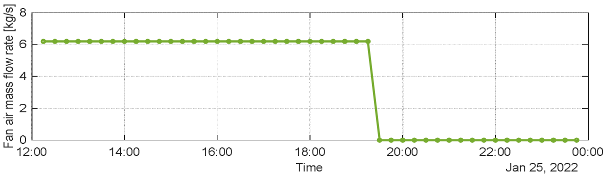

Figure 7: Constant fan coil air flow rate according to digital twin simulation.

The setpoint temperature (yellow line), the IAQ sensors values (grey lines), the weighted average value (red line) representing the actual building temperature, and the digital twin calculated temperature (blue line) are demonstrated in Figure 8. Through these experimental results, it is demonstrated that the building digital twin is able to accurately capture the thermal response of the building when the fan coil speed is set to automatic, as shown in Figure 9.

V. USE CASES DEMONSTRATION

Since the building digital twin model accuracy is validated in Section IV, the developed digital twin is trusted to be utilized for investigating and demonstrating the building operation under different use cases. In this section, the building digital twin is used to demonstrate: (a) the impact of an operational fault on a temperature sensor, (b) the building energy management when a battery system is integrated, and (c) the energy management of an actual battery system connected in HIL configuration with the building digital twin.

A. *Operational Faults – Sensor temperature failure*

The first use case investigates how a temperature sensor fault can affect the indoor air quality and energy consumption. An operational fault (e.g., offset fault) of the temperature sensor of the thermostat can lead to a poor energy performance and can create inconvenient environmental conditions for the occupants according to [14]. After investigating the effect of such failures on the building operation, the plan for future work includes the design of intelligent fault diagnosis and accommodation schemes to compensate the undesired impact.

This use case focuses on an offset temperature sensor fault. In such failures, the temperature sensor of the thermostat used for controlling the air temperature of a specific zone reads a value which contains a constant offset deviation from the actual room temperature. In the investigation results presented in Figure 10 and Figure 11, such an offset fault is applied in a selected zone between 12:00 and 16:00 on 23/02/2022, where a -2 ºC offset is added to the actual room temperature. Figure 10 presents the indoor air quality impact when an offset fault occurs. At 12:00, the temperature set-point (blue line) is changed from 24.5 ºC to 23.5 ºC and at the same time a sensor fault occurs. The thermal behavior of the building digital twin is presented with black line in case of a healthy sensor (base scenario), where the HVAC system is almost deactivated to allow the temperature to decrease and reach the set-point. This

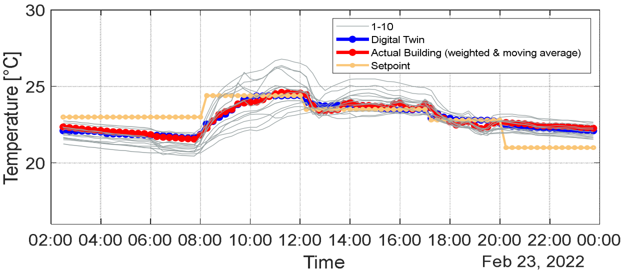

Figure 8: Setpoint and sensors temperture, actual room temperature, and digital twin temperature when fan coil speed is set to auto.

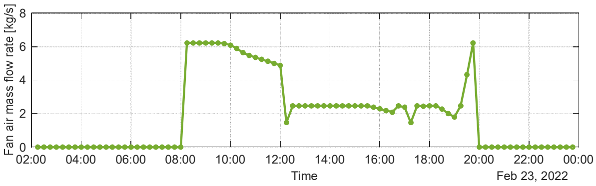

Figure 9: Auto fan coil air flow rate according to digital twin simulation.

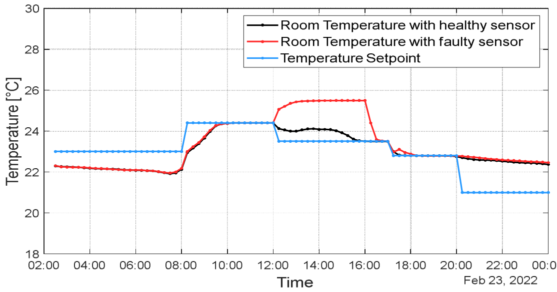

Figure 10: Zone air temperature with health and faulty temperature sensor.

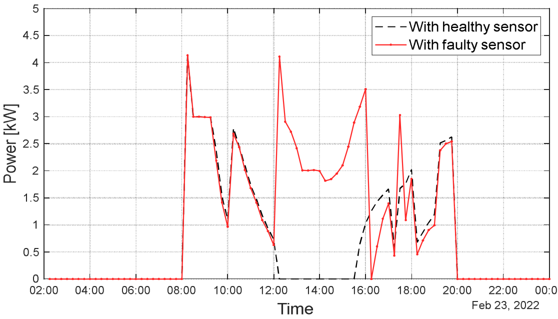

Figure 11: Power consumption with healthy and fault temeperature sensor.

results in a reduced power consumption by the HVAC system as indicated in Figure 11 (black line). The same experiment is repeated with the faulty sensor (red line), where the error in the temperature sensor affects the HVAC system operation and the room temperature is increased violating the comfort zone for the occupants. At the same time, the HVAC system absorb more active power which leads to a higher energy consumption (26.05kWh compared to 17.15kWh of the base scenario). Such a sensor fault can negatively affect both the air quality and the energy consumption of a building and therefore, algorithms able to timely detect and accommodate such faults in building can have a significant impact.

B. Energy management with and without a battery system

The capability of the proposed building digital twin to properly capture the thermal, air quality and electrical operation of the building at the same time enables its utilization for energy management investigations. The energy consumption of the HVAC system to maintain the desired air quality and comfort level for the occupants in combination with the lighting and electrical appliances consumption (according to the user utilization) define the total demand consumption of the building. On the other hand, an 80 kWp PV installation with south orientation and a tilt angle of 33° is considered to partially cover the building energy demand.

In Figure 12, the building electricity demand (red line) is demonstrated for 25/01/2022, where an increased consumption is observed between 09:00 until 19:00 where the HVAC systems, lights and appliances of the building are utilized. The PV generation (green line) is also observed in the same figure for the particular semi-cloudy day with a peak generation of 50 kW. The power exchange with the grid (yellow line) is also demonstrated, where the building imports power (positive value) to cover its energy demand, besides the time window between 07:45 and 13:30 where the excess PV power creates reverse power flow and the building exports power (negative) to the grid. For the particular day, the building imports 189 kWh and exports 74 kWh.

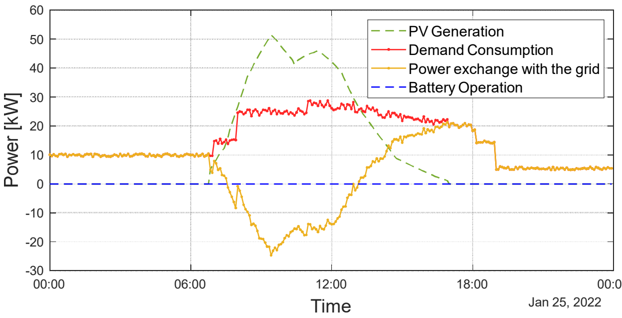

Figure 12: Electricity demand, PV generation and power exchange with the grid without a battery storage system.

In cases where a behind-the-meter battery storage system is available, a flexible energy management can be achieved to increase the self-consumption and reduce the electricity cost. When the building is operating under a net-billing scheme, the export energy is sold in a significantly lower price compared to the purchased price for the import energy. In this context, a battery system can be utilized to increase the self-consumption capability of the building, which reduces the amount of export energy in lower prices and as a result, it can reduce the total electricity cost. In self-consumption mode [15], the battery uses the export power to charge, given that the battery inverter ratings are not violated, and that the battery is not fully charged. Then, the battery discharges to cover the energy demand when the building imports energy until the battery is fully discharged.

The energy related operation of the building is demonstrated in Figure 13 and Figure 14 when a battery system is considered for a flexible energy management. For this investigation a battery system with 60 kWh usable capacity is considered and with the minimum and maximum State Of Charge (SOC) set to 30% and 90% respectively. While the energy demand and the PV generation are the same with the case demonstrated in Figure 12, the battery system operating in self-consumption mode (blue line) is changing the power exchange between the building and the grid (yellow line). Initially, the battery SOC is 80% and the battery is covering the building energy demand until it reaches the minimum *SOC* at 03:45. Then, the building is importing energy to cover the demand until 07:45, where the PV generation creates excess power. From 07:45 until 11:00, the excess power is used to charge the battery (until the maximum SOC is reached). The rest excess power (11:00-13:30) is exported. Then, the energy demand is higher than the PV generation and thus, the battery is discharging to cover the excess demand until it is fully discharged at 17:15. For the rest of the day, the building imports energy to cover its demand.

In this use case with the battery system operates in self-consumption mode, it is observed that the total import energy is reduced to 97 kWh (compared to 189 kWh without the battery) and the export energy is reduced to 22 kWh (compared to 74 kWh without the battery). The utilization of the battery in the energy management of the building reduces the total electricity cost to 22 euro, compared to 40 euro for the case without the battery (assuming a simplified cost calculation with 26 and 13 cent per kWh for import and export energy respectively). In addition, more sophisticated algorithms [16] can be used to minimize further the building electricity cost when a variable pricing scheme is also applied.

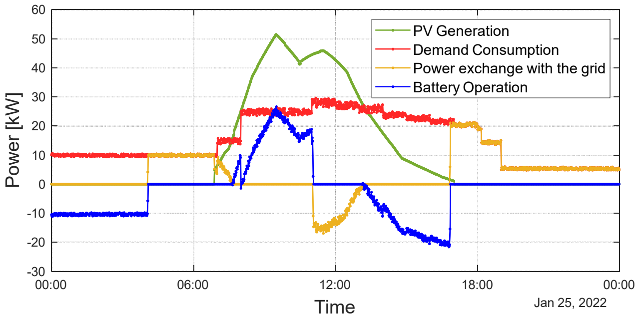

Figure 13: Electricity demand, PV generation and power exchange with the grid, and battery operation (battery emulated within the digital twin).

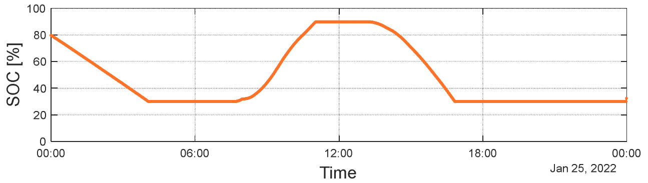

Figure 14: Battery SOC (when battery is emulated within the digital twin).

C. *Hardware in the loop*

The same use case with the previous subsection, is repeated in this section but in this case an actual battery system is connected in a HIL configuration with the building digital twin. An actual LG Chem RESU 10H is installed in the actual building, emulated by the digital twin, and is integrated through a Fronius Symo Hybrid 5 kW. The actual battery is managed by a self-consumption algorithm running as a smart module (in Figure 1), according to the electricity consumption of the building digital twin. Thus, the actual battery, the building digital twin and the self-consumption algorithm are connected in HIL configuration. A scaling factor of 10 is applied in both the inverter ratings and the battery capacity to enable the actual battery to emulate an equivalent battery with 50 kW and 60 kWh (the same with the previous subsection).

Figure 15 and Figure 16 demonstrate the building energy operation with the battery connected in HIL. It is observed that an almost identical operation is achieved compared to results of the previous subsection. The only deviations are the actual standby losses of the battery that have not been considered in the previous subsection, which causes three additional charging instances when the SOC is reduced during noon. In addition, the standby losses lead the battery to a lower SOC than its minimum SOC (30%) during the night. The HIL experiment highlights important information that can be used to improve the operation of the actual battery system before the operation mode is applied in the actual device-building.

VI. CONCLUSION

This paper proposes a novel architecture for the development of a digital twin and an associated software platform for smart buildings able to holistically capture the thermal, air quality and energy (electricity) behavior of buildings. Designed guidelines are provided according to the lesson learned through the development of the digital twin of an actual building. A validation is performed to prove the accuracy of the developed digital twin while different use cases are demonstrated to investigate the impact of sensor faults and of a battery storage system on the operation of a building. In addition, a novel investigation is performed using an actual battery system connected in HIL configuration with the building digital twin.

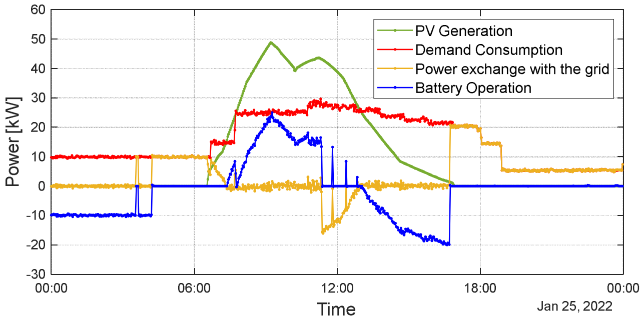

Figure 15: Electricity demand, PV generation and power exchange with the grid, and battery operation (battery and digital twin connected as HIL).

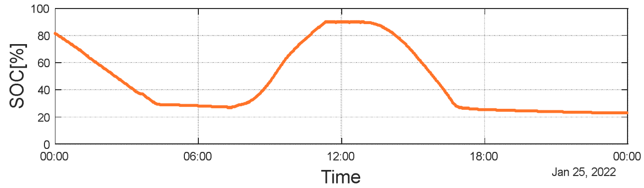

Figure 16: Actual battery state of charge (when connected as HIL).

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