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USER ASSISTANCE SYSTEM FOR SMART COMMERCIAL BUILDINGS – USE CASE AND PROOF OF CONCEPT

Franziska Schranz[1], Vixay Phimmasane[1], Andreas Witzig[1], Andreas Rüst[1], and Daniel Schmid[1]
[1]Zurich University of Applied Sciences, Winterthur, Switzerland

Abstract

Transferring existing buildings with their isolated and heterogeneous systems into the digital world is challenging. Consequently, this paper presents a novel User Assistant System for Smart Commercial Buildings. The demonstrated proof-of-concept on an existing building seamlessly integrates data from various building technologies and validates selected use cases. A wireless IoT sensor network enables the system's services by collecting indoor climate data and tracking assets. Integrated Digital Twins for thermal predictions and modelling of photovoltaic systems (PVS) facilitate dynamic energy optimisation. The results show how to reduce subsystems' operation hours and PVS payback time by providing intelligent, adaptable services.

Introduction

The construction and operation of buildings contribute to around 40 % (United Nations Environment Programme, 2022) of worldwide greenhouse gas emissions. Commercial real estate and especially office buildings significantly contribute to the carbon emissions in the building sector.

An emerging concept to improve the efficiency of a smart commercial building through real-time monitoring and optimisation is the digital twin (Eneyew et al., 2022). This development is possible because of the rise of the Internet of Things (IoT)(Čolaković and Hadžialić, 2018) and advances in building information modelling (BIM) (Azhar, 2011). The Internet of Things and readily available semiconductor chips allow us to equip a building with sensors observing indoor climate and collecting real-time measurements (Khajavi et al., 2019). Whereas BIM contains a full 3D model of the building structure and a wealth of descriptive and operable metadata (Tang et al., 2019). The integration of both technologies into one framework and integrating simulation tools forms a digital twin where real-time and static data are processed to monitor the current state, predict the future state, and take proactive measures to ensure optimal operation of a building (Eneyew et al., 2022). The primary challenge lies in the seamless integration of all components into a unified system that adds value to an existing building.

This project aims to provide the services needed to track sustainability performance and optimise the technical systems based on a digital twin during the operational phase. Three use cases were worked on in which different research questions were answered.

1. Use case 1 addresses the open issue of the integration of physics-based simulation into digital twins. A novel way for a simplified model is proposed.
2. Use case 2 introduces devices which collect real-time data for the digital twin and utilise a new data transfer protocol.
3. Use case 3 aims to optimise profits by combining solar energy production and electrical storage.

The overall project goal is not only to reduce environmental emissions but also running costs. Consequently, digital twin technology helps to map the utilisation of the space and adapt the facility management services to increase work productivity. The entire building ecosystem is addressed, leading to an increase in comfort for the employees and tenants. As validated by McGraw Hill Construction (2010), 79 % of building owners expect green buildings to attract more tenants.

This paper is organised in the following manner. The first section introduces the wireframe of the user assistance system and discusses the requirements for interaction with the different stakeholders of a building. The second section presents the three above-mentioned use cases. This is followed by a general conclusion.

User Assistance System

Wireframe

The user assistance system, shown in Figure 1, is connected to the existing building infrastructure systems, e.g. the HVAC (Heating, Ventilation, Air Conditioning). It consists of a dedicated Graphical User Interface (GUI), a control system comparable to industrial control systems on a PLC and SCADA level (Programmable Logic Controller, Supervisory Control And Data Acquisition (Heinrich et al., 2017)), and a connection to simulation tools, such as Simulink to compile sophisticated simulations. Besides the data and information of the existing subsystems, other sources are connected to the control system, e.g., the weather forecast (global radiation).

For the pilot building and demonstrator "eliona" (Leicom AG, 2023) has been chosen as the GUI. Via this GUI the customers can access the running control loops as applications. Therefore, the interaction with building subsystems and additional running applications takes place at

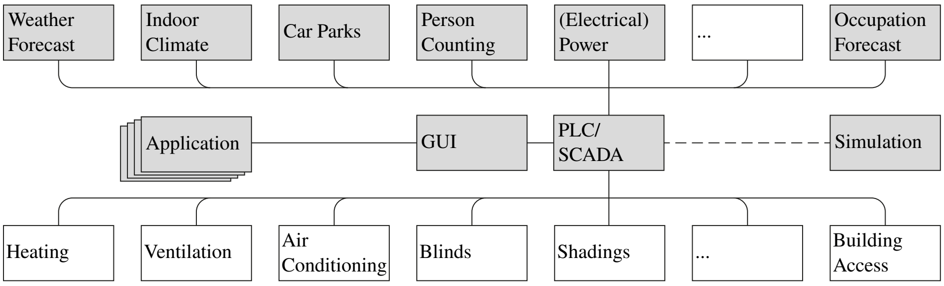

Figure 1: Wireframe of the User Assistance System For Smart Commercial Buildings. Grey: Data newly brought to the building and applications running on the PLC. Simulations are done with COMSOL for thermal energy optimisation and with Matlab/Simulink for the IoT Network as described in the respective subsections.

one centralised point to ease the building operation and increase efficiency. The BACnet protocol (Merz et al., 2009) has been used to enable bidirectional communication between “eliona” and the building subsystems. Furthermore, it would be possible to connect ”eliona” to an Enterprise Resource Planning (ERP) system in case multiple smart commercial buildings are managed accordingly.

Customer Interaction

A building faces a variety of stakeholders; e.g. energy-related stakeholders are the owner, designer, contractor, supplier, occupant, energy manager, and government (Zou et al., 2018). Therefore, the interaction with them must be established in an ideal manner. This project uses a building for study and work as a development and test environment. Therefore, the main stakeholders are the occupants (students and employees of the University of Applied Sciences), the tenant (University of Applied Sciences), the building owner, and the facility management (covering e.g. energy management). Their interests and interactions differ, and the related user assistance system must serve all stakeholders. Some requirements are listed below

- The building must provide **occupants** with a pleasant indoor climate in all seasons and support their ability to work. In this case, this mainly concerns the staff’s learning, teaching, and working. Interactions, such as event orientation aids, must be simple and intuitive. This applies to both entering and receiving information.
- The **building owner** wants a property that maintains or increases its value, and its functions must be attractive to tenants. Accordingly, there must be no problems or complaints from occupants.
- The **tenant** needs a building that meets the needs of its customers and staff. In addition, rent and operating costs, e.g., for energy, must be economically justifiable. Additional functions, such as access control and communication networks, must be available and maintainable.
- **Facility management** wants to maintain the building efficiently and effectively, respond to changes in occupants’ needs, and have centralised system access when interacting with the building (heating, ventilation, air conditioning, HVAC) and not have to access many user interfaces.

Furthermore, all stakeholders have in common that the smart commercial building shall be adaptable to their future requirements. Therefore, new applications that create benefits in the efficiency and effectiveness of the building have to be enabled in a cost-efficient and time-saving way.

Use Cases and Dedicated Applications

The following subsections summarise various aspects of the digital twin that have been addressed in this project. Following a user-centric approach, the use cases have been identified first and specific features have been developed in consequence.

Use case 1: Thermal Simulations for a Reduction of Energy Consumption

The building user and the operation manager both play important roles in the energy optimisation of a building. (Buildings Performance Institute Europe (BPIE), 2016). In the use case of thermal optimisation, we investigate which new methods and tools are beneficial for them. Many decisions in optimising and running the energy system can be supported by a physics-based dynamical model. The input data for the calculation as well as the simulation result are by definition a part of the digital twin framework. Simulations predict the effectiveness of energy-saving measures while guaranteeing indoor comfort and are a good basis for facility management to make decisions and optimise HVAC systems.

Simulation Tools

Today’s software tools for simulating buildings cover a wide range of complexity from compact zero-dimensional models to complex physics-based 3-dimensional ones. As an integrated part of model predictive control systems, compact models may be integrated into the energy management systems (EMS). More sophisticated models are typically only applied in the planning phase because those simulation tools are often too elaborate for usage in facility management. Comprehensive modelling of heat storage by the building structure and heat loss through walls and thermal bridges would however make it possible to minimise the building’s energy consumption and reduce construction costs. Given the construction and operating costs, the investment in careful planning would be worthwhile.

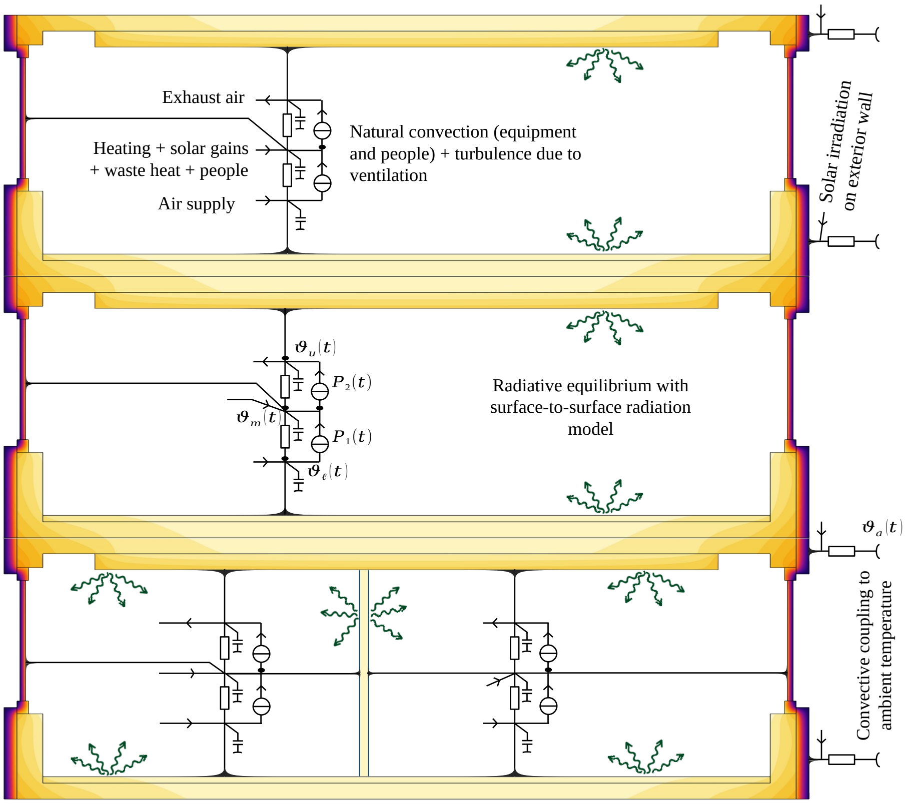

Figure 2: Results of the Finite Element Simulation of the concrete structure. The temperature profile ranges from yellow (23°C room temperature) to dark blue (ambient temperature $\vartheta_a(t_0) = 4°C$). The Figure additionally shows a schematic visualisation of the lumped element model for the air domain with a temperature at an upper, middle and lower node ($\vartheta_{u,m,l}$) and an energy flux between the nodes and the energy fluxes coupling the system to the environment.

Integrating Simulations into the Digital Twin

This work proposes to integrate comprehensive physics-based simulation to support the operation of buildings. Continuous synchronisation with sensor data ensures that the simulation is close to reality. Simulation results need to be translated into a building management cockpit to generate added value for facility management.

To integrate physics-based simulation in the digital twin, two challenges have to be addressed: First, translating the a priori information from building plans into the physical model cannot be done automatically yet. The process includes tasks like identifying walls from complex geometries and estimating heat loss parameters. Secondly, the relevant information for facility management has to be automatically post-processed from the simulation output.

Building information modelling (BIM) has greatly advanced in the last few years (Tang et al., 2019). The digital representation of a building is now ready to contain a variety of parameters and a full 3D model. Together with the immense increase in computational power since the design of our state-of-the-art tools, this creates great potential for new simulation approaches.

This work proposes a finite-element discretisation for the building structure. It uses a simulation domain closer to the BIM representation and relies on physical material parameters. The approach has the potential to reduce the effort for the translation from BIM to the simulation model. It aims to provide detailed information about thermal-electric interactions in buildings considering thermal capacity.

Model Description

We envision in the long-term a full 3D simulation of the concrete structure, where the U-values and thermal bridges result directly from material parameters and the building geometry. In our current version, we apply 2D numerical simulation of the concrete structure to save computational resources. This will prove the concept of getting more insights into the interactions between building fabric and energy flows in buildings.

In addition to the heat flow in the solid structures, radiation between the walls is accounted for, resulting in realistic surface temperatures. Airflow in the rooms is approximated by a lumped element model with three dynamical nodes per room. This is in contrast to full 3D fluid dynamics simulations, which have both the drawback of extremely high usage of computational power and a requirement for more knowledge of the occupancy and the user behaviour.

The dynamic model also contains the control algorithm for the HVAC system and predicts the net primary energy consumption for heating and cooling of the building for any time period. Variants of energy-saving measures can be compared and evaluated yearly with the use of a stochastic model for the outside weather conditions and user behaviour. Witzig et al. (2023) present the detailed model description.

FEM Simulation Setup and Results

With COMSOL Multiphysics we simulate the ground floor of the three-storey building shown in Figure 2 on a relatively coarse mesh. The floor is 2.4 m high and 5 m wide with windows on each side and has a partition wall separating it into two rooms. Sunshine is only assumed in the right room (heading south). Periodic boundary conditions are imposed at the top and at the bottom of the simulation domain for simplicity.

Simulations first solve for a stationary solution, which is the initial condition for the transient study. Solar radiation, outside temperature and thermal loads from people and electronic equipment are inputs to the model.

The coloured area in Figure 2 shows the temperature profile ranging from yellow (23°C room temperature) to dark blue (ambient temperature $\vartheta_a(t_0) = 4°\mathrm{C}$). The HVAC system has turned off and no automatic sunlight shading is assumed.

Discussion

It is important to see that thermal loss through the building shell is calculated accurately with the full dynamics of the building structure, including the thermal storage capability of the building structure. Solar irradiance on the south façade does contribute to the heat balance of the building (although it is minimal in the presented example because the outer layer of the wall is insulating). It is not necessary to introduce U-values as parameters and thermal bridges are naturally solved with adequate precision. The usage of thermal simulation in the energy management system requires an adequate time-dynamic representation which also includes the HVAC system in the model with its controller. The simulation model interacts with the PLC/SCADA and on the one hand, relevant output is displayed in the GUI, on the other hand, automatic action is taken in controlling HVAC and shades (see Figure 1).

Use case 2: Low-power IoT Wireless Network for Sensors and Asset Tracking

Existing commercial buildings typically have a central HVAC system with few sparse sensors to control the room climate. However, this is often inadequate to provide a comfortable environment for the building users while simultaneously minimising energy consumption.

As an example, the building chosen for our demonstrator employs distinct subsystems to independently regulate its indoor climate. Notably, the sensors only measure the actual temperature in the basement's technical room through the exhaust air, but the individual room temperatures are currently unknown. Our experiment shows the retrofitting of such a building through modern IoT devices. The integration of multiple wireless sensors enables more detailed and individualised monitoring of environmental data, including air quality and solar radiation.

Thread Mesh Network

To establish a robust, low-power network for the wireless sensors, we used the standardised Low-Power Network IPv6 Protocol Thread (Thread Group, 2023). Thread uses the 802.15.4 radio to create a low-power mesh network, with the network's resilience increasing as more devices join. Figure 3 shows a typical thread mesh network structure.

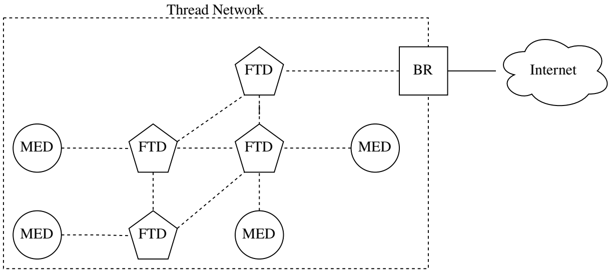

Figure 3: Overview of a Thread Network with Full Thread Devices (FTD), Minimal End Devices (MED) and Border Router (BR)

Full Thread devices (FTD) are miniaturised, permanently powered devices acting as routers. They form a resilient mesh network and provide the communication infrastructure for the battery-operated Minimal End Devices (MED). Typically, FTDs are integrated into objects where power is readily available, e.g. lamps and power outlets. Border Routers (BR) provide the interface of the wireless Thread network to the Internet.

The MEDs are movable low-power devices that connect to the best available FTD. The FTD then forwards the packets to the BR. Typical applications for MEDs are sensors for environmental parameters but also asset tracking tags.

Hardware

For Proof of Concept, nRF52840 dongles (Nordic Semiconductor, 2023) from Nordic Semiconductor with USB power adapters were used as routers (FTDs), and several Raspberry Pis with nRF52840 dongles acted as thread border routers. We developed a sensor node (MED) with nRF52840 SoC as the minimal end device, consisting of the BME680, OPT3001, and LSM6DSL sensors. These sensors are used to measure temperature, humidity, air pressure, volatile organic compounds, and other environmental data. A CO_2 sensor is added as an optional extension. Figure 4 shows the Sensor Node and the nRF52840 dongle. Zephyr RTOS (Zephyr Project, 2023), with the open-source implementation of OpenThread, was used for firmware implementation. The sensor node can be operated with a CR2032 button cell battery, external battery, or micro USB. With a CR2032 battery, the battery life is approximately 600 days for a measuring interval of ten minutes.

Collecting Environmental Data

The sensor nodes collect environmental data at ten-minute intervals. This data is sent to a server via the Thread net-

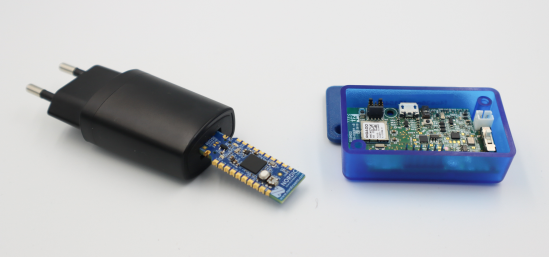

Figure 4: nRF52840 Dongle with USB power adapter (FTD) and a battery-powered Sensor Node (MED)

work, where the collected data is analysed and visualised, providing valuable insight into the usage of the rooms.
In Figure 5, the increased CO_2 concentration in the data indicates lunch breaks in a break room. In Figure 6, the occupancy of a classroom can be identified based on several environmental parameters. The temperature increases due to people and the use of electronic devices such as laptops. The illumination increases due to the use of light, and the CO_2 value increases the longer people are in the room. Further analysis allows us to identify unused or little-used rooms. As a result, the heating of these rooms could be reduced to save energy. In contrast, the HVAC system could increase ventilation in heavily used rooms to enhance people's well-being.

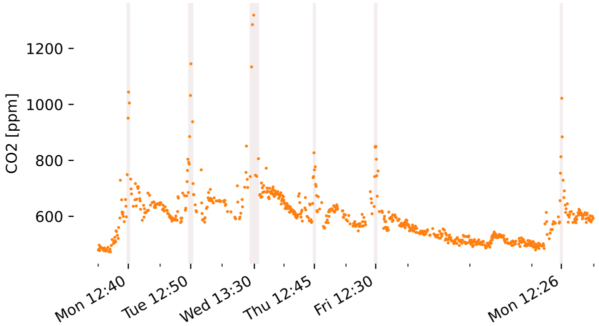

Figure 5: CO_2 concentration in the break room for one week, shaded areas indicate lunch breaks.

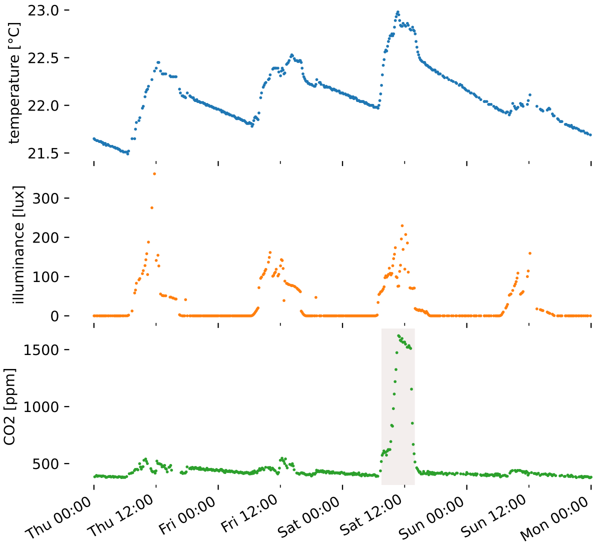

Figure 6: Environmental data of a classroom for four days, creating insight into occupancy.

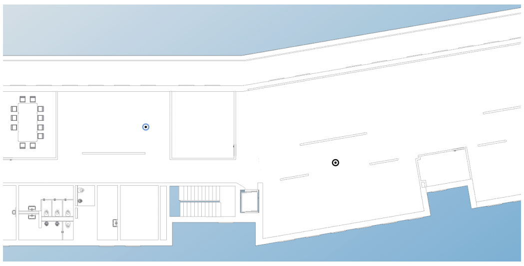

Figure 7: Screenshot of the visualisation on the GUI showing the location of two MEDs.

Asset Tracking using RSSI of Thread Devices

Besides collecting sensor data, we use the dense Network of Thread routers to track movable assets through an attached Thread device. Our experiment shows that this allows assets to be tracked with room accuracy. The routers have a fixed, known position and act as anchor nodes. By collecting received signal strength indicator (RSSI) data from neighbouring devices in the network, the distance in meters to other devices can be estimated using the log distance path loss model.
If the RSSI is high, we assume that the movable Thread device is located in the same room. If the distance is greater, trilateration is used to calculate the coordinates and, therefore, the position in the building. Figure 7 shows an example of the visualisation on the GUI. As a proof of concept, the asset tracking was tested in the demonstrator building on one floor with at least 2 routers installed per room. With 600 attempted localisations, the algorithm was able to correctly determine the room in 75 % of the localisations. In 16 % of cases, the adjacent room was identified.

Application: Controlling the HVAC system

The Proof of Concept has shown that environmental data such as temperature and humidity can be monitored individually in different rooms using a low-power thread network with wireless sensors. The analysis of the collected data allows conclusions about the effective room occupancy and thus the HVAC system can be controlled accordingly to increase the people's well-being or save energy.

Use case 3: Digital Twin For Optimising A Photovoltaic System

The aim is to select the best photovoltaic system (Wagner, 2019) and to optimise its payback period on the related commercial building by applying the digital twin (DT) concept (Crespi et al., 2023) and considering the steadily increasing electro-mobility (Gomes and Imark, 2023). The question to be answered is if a buffer battery, of a specific capacity, can lower the payback period, and to what extent the system's autarchy is increasing. To answer this question a Simulation is performed based on historical data for the building's power consumption, measurement of the car park occupation, the actual and forecasted solar irradiance (global radiation), and the different capacities of buffer batteries. With those data sets, we run the simulation as a live digital twin with different parameters to determine the layout of the optimum photovoltaic system. The following sections describe the elements of the simulation in detail.

Historical Data – Electrical Power Consumption

The energy consumption of the teaching and working building fluctuates strongly between different day characteristics. Configurations have been built to investigate it, consisting of different attributes and attribute values. The attributes are weekdays, lectures, exams, holidays, and seasons.

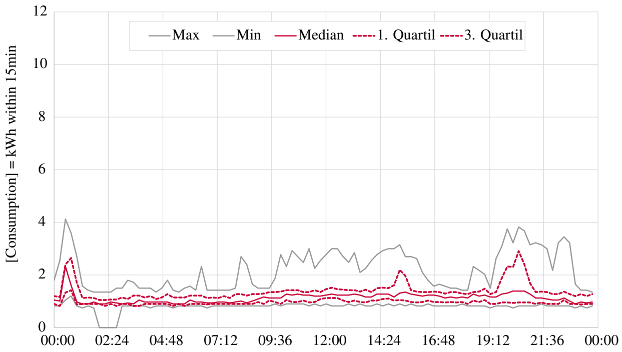

Figure 8: Energy consumption on a weekend with running lectures, no exams and no holidays in spring.

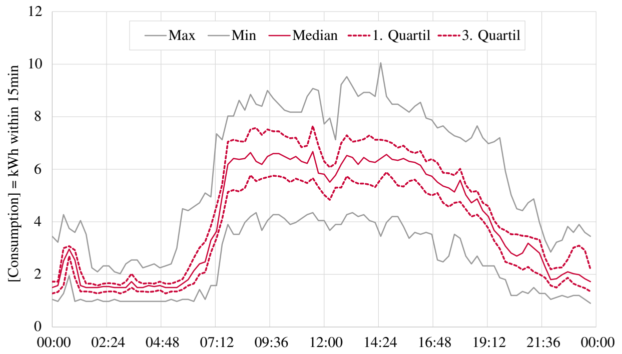

Figure 9: Energy consumption on a working day with running lectures, no exams and no holiday in autumn.

Two significantly different energy consumption patterns are visible in Figure 8 and Figure 9, showing the values over the day as median, first and third quartile and minimum and maximum (no reduction of outliers). Figure 8 shows the consumption during all weekends in the spring of 1 March – 31 May 2021 (median: 108 kWh), while Figure 9 shows the working days during the autumn of 1 September – 30 November 2021 (median: 389 kWh). It is proven that a smart commercial building's energy consumption fluctuates significantly, and a forecast can be made via historical data and related characterised days. The method via characteristic days outperformed the approach via the least-square (LS) method (Swain et al., 1988). The relative error of LS is around 30 % to 50 %, while the characteristic days are around 25 % to 35 %.

Actual Data – Car Park Occupation

The future electro-mobility is anticipated and, therefore, part of the model. The data source is the actual occupation of the car parks monitored by related car park sensors. The assumption is that 4 out of 15 car parks are equipped with vehicle-to-home (Han and Acquah, 2021) capable (V2H) 11 kW charging stations and the related cars placed on the car parks require to be charged and contain 80 kWh batteries (Gomes and Imark, 2023). The system is allowed to charge the battery up to a maximum of 80 % and to discharge it to a minimum of 10 %. The cars arrive with a 50 % charged battery and the system knows when the car is leaving.

Forecast – Solar Irradiance (Global Radiation)

As the photovoltaic (PV) system produces electrical power depending on the solar irradiance (global radiation) and the relative position of the sun to the PV panels, two different forecasts have been analysed. The comparison has been established by comparing the solar irradiance measured by the pyranometer (Apogee SP-212-SS) on the reference building's roof with openly available data (Global radiation measurement, 10 min mean - opendata.swiss) for the related measuring station in 500 meters distance (Homepage - MeteoSwiss). The time resolution for the comparison is 1 hour.

One forecast is based on the assumption that "tomorrow is as today". The standard deviation of the difference between hourly mean measurement and forecast is $12\,\mathrm{W/m^2}$ over the whole day (24 hours) and for all seasons (sample sizes of 3 weeks within the middle of each season). The related average of the error is close to zero.

The second forecast is based on the COSMO model of MeteoSwiss interpolated to the building position. As the forecast is systematically lower than the actual solar irradiance, a correction factor for each season has been determined, bringing the average error to zero. With this correction, the standard deviation of the difference between measurement and forecast is $15\,\mathrm{W/m^2}$. The daily mean global radiation at the building's location reaches up to $369\,\mathrm{W/m^2}$ in 2023.

The accuracy of the solar irradiance forecast is lower than the simple assumption that tomorrow is the same as today. In 2024, the ICON model will substitute the COSMO model, delivering better accuracy, as MeteoSwiss informs.

Additional Infrastructure – Buffer Battery

For the simulation, different capacities of the buffer battery have been considered: 6, 9, 12, and 15 kWh. The local electrical power supplier recommends a capacity of 6 kWh. 9 kWh covers 50 % (median) of the consumption over the photovoltaic system's supply, 15.1 kWh 75 % (third quartile), and 15.6 kWh 84 % (average plus standard deviation).

Digital Twin Framework

The digital twin framework takes all the mentioned elements into its model, running on the industrial control system interfaced with the user assistance system. The market prices in Tables 1 and 2 have been taken as a reference to shorten the payback period (Polysun; EKZ | Privatkunden).

Table 1: Investment cost in CHF

PV System incl. VAT	133,000	133,000
Battery 15 kWh incl. VAT	+12,000	0
State subvention	-14 %	-14 %
Tax savings	-15 %	-15 %
Total	106,700	97,300

Table 2: Electricity prices

Self consumed electricity incl. maintenance (CHF 0.04/kWh)	0.232 CHF/kWh
Selling during high-rate tariff time	0.084 CHF/kWh
Selling during low-rate tariff time	0.074 CHF/kWh

Analysis of the payback period and autarchy

The simulation results are summarised in Table 3. A system can achieve the shortest payback period of 10.3 years without a buffer battery but with active management of charging electric vehicles based on the solar irradiance forecast. The period might be shortened when the ICON model substitutes the COSMO model, depending on the costs of the data.

A buffer battery of 15 kWh capacity would increase the building's autarchy by 3 % points and lift the payback period by 4.5 months. The autarchy would rise further with higher buffer battery capacities.

If no forecast of the solar irradiance is considered, the payback period is 7 months longer compared to the optimum. The degree of autarchy is reduced by 2.5 % points.

A smart commercial building benefits from a digital twin framework to optimise a photovoltaic system. The related modelling, simulation, and communication can run on the central user assistant system.

The photovoltaic system's payback period of 10.9 years is shortened by around half a year to 10.3 years. In the case of the selected reference building, the investment costs are CHF 97,300 (without battery), and the payback period ends CHF 5,300 earlier. The conclusion is that only for large photovoltaic systems active management by applying a live digital twin framework makes economic sense.

Table 3: Simulation results for the payback period and autarchy, depending on battery capacity and active management of charging electric vehicles based on the solar radiation forecast

Battery	Forecast	Payback period	Autarchy
-	yes	10.3 yr	38 %
15 kWh	yes	10.7 yr	41 %
-	no	10.9 yr	35.6 %

Nevertheless, the described digital twin enabled a photovoltaic system optimisation based on real-life data.

Conclusions

In summary, this work demonstrates how multiple use cases collectively advance the domain of smart building technologies by the fact that they are integrated into a holistic digital twin. The thermal simulation is instrumental in achieving energy efficiency by dynamically adjusting building operations, leading to significant savings and enhanced occupant comfort. The IoT wireless network introduces a paradigm shift in environmental monitoring and asset management, enabling precise control over space usage and energy conservation. In addition, the same adaptive and robust IoT network can be used for asset tracking, which - embedded in a corresponding business model - makes everyday office life more efficient. Furthermore, it has shown that it is beneficial to integrate the PV systems into the digital twin, thus balancing out energy production and consumption and thereby accelerating the return on investment and promoting environmental sustainability. It is evident that the three use cases are interwoven and support each other: Thermal comfort is optimised based on sensor data with room precision, anticipating office activity and using electricity from the local PV system. Overall, operating costs can be reduced while at the same time reducing the impact on the environment. These applications not only showcase the potential of smart technology in transforming building management but also underline the importance of such innovations in the broader context of sustainable development and energy conservation.

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