Information and Communication Technologies (ICT) for the Intelligent Operation of Building Energy Systems: Design, Implementation and Evaluation in a Living Lab

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Abstract

Successful adaptation to climate change requires resilient, reliable, and efficient energy systems. To unlock energy efficiency potentials in buildings, an intelligent, user-centered approach is vital. However, this requires handling diverse data on the energy system. Therefore, technologies for harmonizing, storing, and visualizing data, as well as managing physical devices and users are needed. This work assesses existing and required Information and Communication Technologies (ICT) for intelligent building energy system operation. We propose an intermediate architecture based on Internet of Things (IoT) core principles and feature insights from its implementation within the Living Lab Energy Campus (LLEC) at Forschungszentrum Jülich. We present an approach for integrating existing ICT components, such as building energy metering and central Heating, Ventilation and Air Conditioning (HVAC) management, and propose a comprehensive data collection and distribution infrastructure. We establish IoT-enabled applications for energy system monitoring, user engagement, advanced building operation, and device identification and management. We evaluate our ICT setup through functional and performance assessments. We find that heterogeneous data can be reliably collected, distributed, and managed using standardized interfaces, state-of-the-art databases, and cutting-edge software components. For the buildings operated through the ICT infrastructure, data transmission availability is above 98.90 %, mean time to repair (MTTR) is less than 2.68 h, and mean time between failures (MTBF) is in the range of 242.67 h to 1092.00 h, evaluated over a period of three months. Our approach promotes the early real-world adoption of intelligent building control prototypes and their sustainable development. We demonstrate the proposed ICT setup through an experimental study that applies a cloud-based Model Predictive Controller (MPC) to a real building space. Our results provide a comprehensive discussion of the required ICT setup for intelligent building energy system control in real-world environments, and highlight important design strategies that reduce the conceptual overhead and facilitate implementation in similar projects.

Keywords: Information and Communication Technologies (ICT), Internet of Things (IoT), Smart Sensors, Data Acquisition and Management, Edge Computing, Building Energy Systems, Model Predictive Control (MPC), Living Labs

1 Introduction

Despite ongoing major efforts to slow global warming, annual CO_2 emissions continue to rise steadily [1]. More than 50 % of global emissions come from electricity supply, heat generation, and the building sector [2], with the building sector being particularly important, accounting for around 30 percent of total final energy consumption [3].

From a design perspective, energy-related CO_2 emissions in buildings can be reduced, for example, by retrofitting measures [4, 5], by coupling the buildings with (decentralized and renewable) energy supply and storage plants through a microgrid [6–8], by exploiting waste heat via district heating [9–11] and cooling [12] networks, or through wastewater heat recovery [13]. Regarding operation, the energy demand of buildings is primarily determined by occupancy, building use, and the selected operating strategy [14]. Advanced building control concepts such as model predictive control (MPC) can determine optimal operation set-points based on the predicted behavior of the building, taking into account technological constraints, expected occupancy, and weather forecasts [14, 15]. MPC reportedly achieves energy savings of up to 30 % compared to conventional rule-based control (RBC) [14–17] while reducing perceived discomfort [18, 19] and enabling flexibility through load management and load shifting [14, 20, 21].

In addition to the underlying control strategy, building occupants also play a decisive role. They influence the final energy consumption [22], for example, by adjusting the heating set-points, manually operating windows, blinds, or by using or not using electrical appliances, lighting, etc [23–25]. It is therefore crucial to raise occupants' awareness of their energy usage patterns and the resulting impact on energy efficiency [26]. Such feedback to occupants can be provided in different ways, for example, via simple thermostats, advanced human-machine interfaces (HMIs) at room or zone level, tailored dashboards, or web applications [27–29]. Interaction with HMIs can differ significantly and satisfy users to varying degrees, resulting in unrealized energy savings potentials [30]. Accordingly, a thorough understanding of user behavior and the integration of users into the operation of buildings can reduce the carbon footprint of buildings.

Real-world adoptions of intelligent building control strategies are frequently impeded by the fact that they involve a multitude of stakeholders from different domains [31]. To apply a controller and enable energy monitoring, a connection to the building must be established. This can be done by interfacing either the building's Building Management System (BMS) or the underlying Building Automation and Control System (BACS) [14]. Both systems are generally under the maintenance jurisdiction of the building operator or facility manager. Access to these systems may require the establishment of fallback control plans [32, 33]. Additionally, a field-level infrastructure may be needed to collect data from devices that have been retrofitted for the purpose of extending the monitoring and control features [34, 35]. This typically requires careful coordination between researchers and building operators [36]. Finally, all devices, tools, and applications used to evaluate user interactions or input must be integrated [37]. This requires the additional involvement of the occupant groups concerned and leads to increasingly decentralized and network-based building automation systems [38]. In this regard, a modern Information and Communication Technologies (ICT) infrastructure can facilitate the flexible, scalable, and robust exchange of data among the different stakeholders and foster the application of advanced control and user engagement strategies [39, 40].

In this study, we present insights into the design process of an ICT infrastructure that enables the adoption of user-centered building operation concepts within a large-scale living lab. We concentrate on architectural, infrastructural, and technological aspects and provide comprehensive explanations of implementation concepts and workflows. Our goal is to streamline the process for future (living lab) projects by addressing and overcoming potential challenges.

The remainder of this work is structured as follows: In Section 1.1, we provide an overview of previous research in the field of user-centered, model-based control of real buildings and derive the need for a flexible, scalable, and Internet of Things (IoT)-enabled ICT infrastructure. In Section 1.2, we summarize the requirements for such an infrastructure and outline the contributions of our work. Section 2 portrays the existing ICT infrastructure of the site of Forschungszentrum Jülich, defines an IoT reference architecture as the core structure of the ICT setup, and assess the required ICT extensions. In Section 3, we present the proposed ICT infrastructure and its components, emphasizing crucial interfaces and interconnections. In Section 4, we give an overview of the resulting ICT architecture and assess its advantages, disadvantages, and the lessons learned. Finally, we evaluate and demonstrate the operational performance of the ICT infrastructure based on a three-month data throughput analysis and the application of MPC to a real-world building space. Section 5 summarizes our findings, contains concluding remarks, and exposes directions for future research.

1.1 Related Work

The following sections discuss recent publications in the fields of user-centered building operation, infrastructures for connecting buildings to intelligent control systems, and living labs as environments for energy research.

1.1.1 Intelligent Building Operation

Both user engagement strategies and model-based building control approaches were investigated under real-world conditions [19, 28, 41–45]. However, large-scale real-world studies on controllers that incorporate user preferences and provide feedback to users are sparse. Approaches towards the incorporation of user preferences were made by Hilliard et al. [19] who employ a web-based tool to collect occupant feedback on the comfort-related MPC performance. Similarly, Winkler et al. [32] collect votes on the current level of thermal comfort through a web-application and incorporate this in their control approach. West et al. [46] use comfort feedback collected from users via an online tool to fine-tune the thermal comfort model in the MPC. Goyal et al. [47] compare two different MPC applied to a variable air volume (VAV) system supplying single zones. They find that occupancy-informed MPC can outperform RBC when real-time presence, or more importantly, the number of people in the room, is available.

However, neither the control method nor the set-points could be adjusted, which makes operation quite confusing for building users. This can also lead to efficiency losses due to ill-considered actions by frustrated users [30]. Studies like the reviewed ones are typically confined to a small set of or individual buildings and uniform building usage or occupancy patterns. Their transferability and statistical validity is therefore limited.

1.1.2 Connecting Buildings and Controllers

To fully unlock the potentials of user-centered building operation, a sophisticated ICT infrastructure must be established [48]. Per definition, ICT constitutes "the capture, storage, retrieval, processing, display, representation, presentation, organization, management, security, transfer, and interchange of data and information" [49]. This explicitly includes, e.g., "computers, the Internet (websites, blogs and e-mails)" or "live broadcasting technologies (radio, television and webcasting)" and "recorded broadcasting technologies (podcasting, audio and video players, and storage devices)" [50]. Applied to buildings, ICT primarily encompasses the buildings' BMS or BACS but also all digital, analogue, physical, or virtual interconnections to subsystems including measurement equipment, actuators, and HMIs.

Looking at current examples of the use of advanced controls in real buildings, these are usually either directly connected to the existing BMS [44, 51, 52] or BACS [19, 43, 53, 54]. Only a few real-world studies were conducted that use a more elaborate communication infrastructure, e.g., Narayanan et al. [55] deploy field-level sensors via wireless networks and connect them to an existing BACS. Ferreira et al. [41] combine an interface to the BACS with a database that collects data from a separate Heating, Ventilation and Air Conditioning (HVAC) sensor network to apply remote control. In [56, 57] a remote controller is interfaced with the building's BACS via the internet and Drgoňa et al. [33] connect a remote controller to the building's BMS via a cloud-based SCADA system. Blum et al. [35] connect an MPC via a database using interfaces to an existing BMS, a system for monitoring power consumption, a weather service, and a small number of additional wireless sensors. All of these studies report a considerable implementation effort for building interfaces to the BMS. Blum et al. [35] find that the implementation effort was even greater than the effort required to develop the MPC. This is confirmed by West et al. [46] and Winkler et al. [32], who additionally identify significant performance bottlenecks when interacting via the BMS interface. With regard to connectivity in the context of building automation, the potential of the Internet of Things (IoT) [58, 59] as a sub-area of ICT [60] has not yet been fully exploited [39, 40]. Storek et al. [61] coupled the BMS of an existing building to an IoT platform based on FIWARE [62] to enable in-depth energy monitoring. Blechmann et al. [63] apply a remote MPC to a real-world heating supply system via the public internet. However, both studies are small-scale experiments limited to single zones or individual buildings. In summary, there are still many unanswered questions regarding the practical implementation of a comprehensive IoT-enabled ICT infrastructure. This includes both the integration of existing systems and the use of new technologies at all levels between field devices and applications for intelligent building operation.

1.1.3 Living Labs

Living labs can be a game-changer to accelerate research as they bridge the gap between experiments on a test-bed scale and real-world scenarios [64, 65]. They play a key role in validating theoretical energy reduction potentials of different control or user engagement approaches and provide an authentic environment for investigating occupants' behavior and comfort preferences [31]. Besides, living labs often offer heterogeneous building archetypes and usage patterns which enables a comparison of different approaches regarding their robustness, performance, and transferability [36]. An exemplary energy living lab is the *Energy Lab 2.0* project at the Karlsruhe Institute of Technology (KIT) [66]. The scope of the living lab encompasses the intelligent linking of different energy generation, storage, and delivery options. Within the

Energy Smart Home Lab (ESHL), another living lab at KIT, household energy savings through CO_2-budgets are explored [67] and advanced control algorithms are applied to a building test-bed [68]. The *iHomeLab* of the Lucerne University of Applied Sciences (LUAS) focuses on applied research to increase the energy efficiency, security, and comfort in buildings, tackling, e.g., the interoperability between smart building and smart grid technologies [69] or forecasting of electric loads in the residential building sector [70]. The cross-border European Living Lab *ENERGISE* [71] looks at energy-related behavior from a different angle, investigating how to reduce the energy consumption of 306 households by rethinking existing social norms. A comprehensive review of living labs related to human indoor comfort studies can be found in [31]. However, large-scale living labs for the evaluation of advanced, user-centered, and IoT-based building control do not yet exist. Efforts are being made to close this gap as part of the *Living Lab Energy Campus* (LLEC) at Forschungszentrum Jülich.

1.2 Contribution

In light of recent work, we recognize that the real-world application of advanced control algorithms has been tested and evaluated in various studies. These range from the use of prototype interfaces for existing building automation systems to separate sensor networks and SCADA architectures, some of which also follow IoT principles. Investigations are carried out in test rooms or zones, parts of buildings, or, in individual cases, across buildings. The studies mainly focus on one aspect rather than a holistic view of ICT infrastructure, building control and user integration. Several large-scale living labs already exist to improve indoor comfort and analyze energy-related user behavior. However, there are very few such living labs for validating intelligent building control concepts. This leads to the following requirements for further research in the field of intelligent building operation:

- Advanced control strategies should involve as much users and user interaction as possible, support feedback, and offer the occupants flexible options for input.
- The integration of advanced monitoring and control with real-world buildings in a sustainable and cost-effective manner is imperative. This integration must build upon well-established ICT and exploit the flexibility and scalability potential provided by IoT fundamentals.
- To obtain robust control performance benchmarks, the evaluation of theoretically investigated control concepts must be conducted in an ideally heterogeneous and preferably large-scale environment that reflects real-world conditions.

This paper addresses these requirements by making the following contributions:

- We present a flexible ICT infrastructure designed based on core IoT principles and technologies. We demonstrate how the ICT infrastructure integrates with existing building energy metering and HVAC control systems.
- Based on the comprehensive retrofitting of field-level sensors and actuators in [36], we provide a detailed explanation of the data collection, harmonization, storage, and distribution process. Additionally, we propose an approach for managing devices and their associated metadata. We also present ICT-integrated applications for advanced control, monitoring, and user engagement purposes.
- We complement our work with an in-depth functional evaluation of the resulting ICT setup, and discuss its performance based on a three-month evaluation period conducted in a large-scale living lab of 13 mixed-use buildings. Finally, we demonstrate the application of a real-world MPC to one of the on-site buildings using the proposed ICT components.

2 Background

In this chapter, we provide relevant background information for this paper: Section 2.1 describes the scope of the related living lab project. Section 2.2 presents the energy-related ICT components that were already in place before the start of this study. In Section 2.3, we propose an IoT reference architecture for the ICT infrastructure. Lastly, in Section 2.4, we highlight the additional ICT functionality required to enable intelligent building operation.

2.1 The Living Lab Energy Campus (LLEC)

The *Living Lab Energy Campus* (LLEC) establishes a real-world laboratory environment on the premises of Forschungszentrum Jülich GmbH (FZJ) [72]. In the course of the project, various energy demonstrators have been installed on the campus, including liquid and gaseous hydrogen technologies [73, 74], lithium-ion batteries, photovoltaic systems, and district heating (DH) networks [10, 11, 75–77]. Furthermore, a central goal of the LLEC is to establish a test-bed for the investigation of novel, user-centered monitoring and control approaches for building energy systems. For that purpose, a heterogeneous set of 13 existing buildings has been retrofitted with additional sensors and actuators at both room and building level [36].

2.2 Existing ICT for Building Monitoring and Control

Two ICT components for building monitoring and operation existed before the start of the LLEC project: a digital energy metering system for billing data and a system for decentralized HVAC operation management. These systems provide a basic infrastructure for building-level monitoring and control, making them an important source of information. Establishing interfaces to these systems allows for insights into building energy consumption and operation strategies.

2.2.1 Building Energy Metering

The Technical Building Operation Department (TBOD) operates FZJ's energy metering system for building energy and media consumption. Over 1,200 meters are installed and connected to the site-wide system. Recording of energy and media consumption, e.g. to monitor energy-intensive processes, occurs in some cases. Data is used to localize potential savings, review energy optimization measures, allocate energy costs, and comply with reporting obligations.

At the field level, an M-Bus [78] based infrastructure is used. The bus connects meters for grid electricity, heat from a DH network, cooling and tap water, Figure 1. M-Bus meters are located at the buildings' main connection points, as well as in sub-distributors and heating hubs. For some buildings, additional meters are installed to enable more precise allocation of consumption. Energy suppliers, e.g., photovoltaic plants, are metered either separately or together with the associated building. Such a metering setup is typical for research facilities, industrial properties, and mixed-use neighborhoods, especially if critical processes have to be monitored.

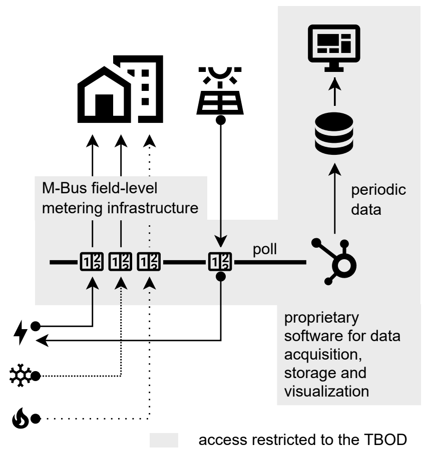


Fig. 1 Building energy metering infrastructure operated by the Technical Building Operation Department (TBOD).

The M-Bus infrastructure is connected to a proprietary commercial energy management system. The system implements a polling mechanism to retrieve data from the M-Bus meters and store the data in a central database. Typically, a standard polling interval of 60 s is used, resulting in minute-by-minute data for the over 10,000 data points available. Access to the system and the underlying database is restricted to the TBOD.

2.2.2 Building HVAC

The site's DH network, operated at approximately 100 °C, provides process heat and heat for space heating. Heat is exchanged at the buildings' main connection points via heat transfer stations and subdivided according to the local heating systems. Most buildings have heating systems based on high-temperature hydronic radiators. Labs and newer buildings use air handling units, e.g., in combination with thermally activated building structures (TABS). In addition to the heating network, there are two cooling networks. Being fed from a local stream, the first network has a higher, seasonally fluctuating flow temperature and varying cooling power. The second network has a lower flow temperature, higher cooling power, and is fed by dedicated chillers. Cooling power is consumed via transfer stations at the building level, similar to heating.

The buildings' HVAC systems are centrally operated, maintained, and managed through FZJ's Building Automation and Operating Services Department (BASD), Figure 2. Each building is equipped with a Direct-Digital-Control (DDC) device that controls HVAC components via field buses. These local controllers implement basic logics (e.g., heating curves or basic operation status checks). A supervisory management system enables central access to all installed HVAC hardware. Both the local controllers and the central management system use BACnet/IP [79] as the communication protocol. In addition to providing control functions, the local controllers act as gateways from field level sensors (e.g., flow or return temperature sensors) and actuators (e.g., mixing valves) to the central management system by converting the physical

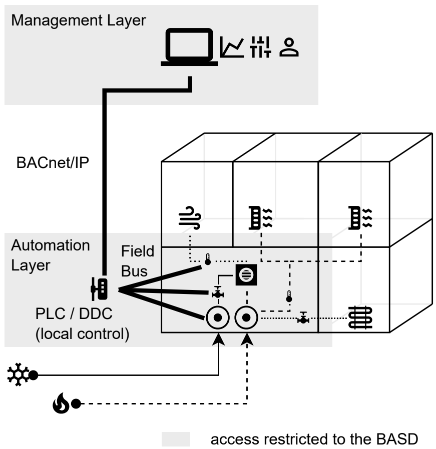


Fig. 2 Hierarchical HVAC management infrastructure operated by the Building Automation and Operating Services Department (BASD).

I/O signals to BACnet/IP data. This BACnet/IP-based infrastructure for HVAC is embedded in a sub-net within the campus LAN. HVAC monitoring, configuration, and control is restricted to the BASD.

2.3 IoT Reference Architecture

Our goal is to embed both existing and new ICT components into a comprehensive ICT infrastructure based on IoT principles. When using IoT principles, a reference architecture is often established to define certain IoT layers, as a universal definition is difficult to find [80]. As pointed out by Alfalouji et al. [81], there are different views on the components of an IoT architecture depending on the background of the researchers. According to Farahzadi et al. [82] and Da Cruz et al. [83], an IoT architecture may consist of the three basic layers which are *devices and infrastructure*, *IoT platform*, and *users or applications*. Three layers were also proposed by Jia et al. [84] and Domingo [85]. However, different categories were used to describe the layers, namely *perception*, *network*, and *service*. An IoT architecture consisting of four layers was proposed by Patel and Patel [86], using the layers *smart devices*, *gateways and* *networks*, *management service*, and *application*. A five-layer model comprising *perception*, *network*, *middleware*, *application*, and *business* was suggested by Antão et al. [87]. In general, IoT reference architectures with a number of layers between three and seven can be found in literature [88, 89].

Based on the existing reference architectures and the scope of the LLEC, we have derived a four-layer model comprising the categories *operational technology*, *edge*, *data distribution*, and *users and applications*. The purpose and capabilities, as well as example technologies for each layer, are given in Table 1.

Table 1 Proposed four-layer IoT reference architecture.

Layer	Purpose and Scope	Technologies
Users and Applications	• manage devices • collect user preferences • provide feedback • energy monitoring • analysis tools • advanced controllers	web-applications, interactive dashboards, research frameworks
Data Distribution	• access data • distribute data • persist/store data	networks, interfaces, brokers, databases
Edge	• collect data from field devices • harmonize data streams	gateways, edge adapters, data models
Operational Technology	• obtain measurements • manipulate the environment	sensors, actuators, panels

2.4 Functional Requirements for the ICT Infrastructure

Based on the research directions identified in Section 1.2 and the IoT reference architecture introduced in Section 2.3, functional requirements for the design of the ICT infrastructure are derived in the following.

2.4.1 Operational Technology

At the start of the project, room-level measurements and control were not available in any of the LLEC buildings. However, monitoring indoor air quality and occupant comfort indicators is crucial to understand energy consumption and increase efficiency. Sensors to measure temperature, humidity, and CO_2 concentrations or track window openings to derive ventilation patterns, as well as actuators for room automation (heating, shading, and lighting) had to be retrofitted. The selection of field-level technologies and the retrofitting process have been published in [36]. Therefore, with respect to operational technology, this paper will cover only the integration of field devices with other ICT components.

2.4.2 Edge

Due to the different requirements in the multiple domains and the multitude of building types, various field-level communication protocols and a mix of wired and wireless components are required. These additional sensors and actuators in the buildings require an additional edge device, i.e., a gateway, that must be introduced as an interface between the field and the data distribution layer. The gateway must offer the possibility to harmonize and standardize different data streams to one format, e.g., through (object-oriented) data modeling. Finally, it must be easily extendable in terms of hardware interfaces and supported protocols.

2.4.3 Data Distribution

In the data distribution layer, data distribution and data persistence entities must be established. Data persistence services are required to store time-series data streamed from the gateways and to hold relational data, such as device or location information. Distribution technologies are required to transport data from one entity to another, such as between application layer entities. Depending on the nature of the communication between entities, either client-server (e.g., HTTP [90]) or publish-subscribe (e.g., MQTT [91]) protocols are suitable.

2.4.4 Users and Applications

This layer includes all the applications required for IoT-based intelligent building control in a real-world environment. Applications can be divided into two categories, management-oriented and research-oriented. Management-oriented applications include the following:

- **Device identification**, acquisition of metadata and its accessibility.
- **Device management**, including physical and virtual representations.
- **Modeling of device data** for harmonization and easy discovery.

Research-oriented applications cover the following:

- **Data visualization, analysis, and pre-processing** for data quality analysis, operation monitoring, and fault detection.
- **User engagement** by revealing concealed energy flows, communicating wasteful energy-consumption patterns, and collecting comfort preferences.
- **User input management** to derive set-points to be tracked by controllers.
- **Advanced control**, e.g., MPC for HVAC or shading systems at both building and room level.

The next section details the integration of existing components and the development and implementation of additional ICT components to establish a comprehensive infrastructure for the real-world adoption of intelligent building operation strategies. This includes IoT-ready software prototypes for both management-oriented and research-oriented tasks.

3 Methodology

In this section, we provide an in-depth description of our implementations, including infrastructure, architecture, and software prototypes for accessing data, deploying and managing devices, handling data, incorporating user input, and providing feedback. First, we describe the integration of existing ICT parts, then the methodology for design and implementation of additional components. A general overview of this chapter's contents can be found in Figure 3.

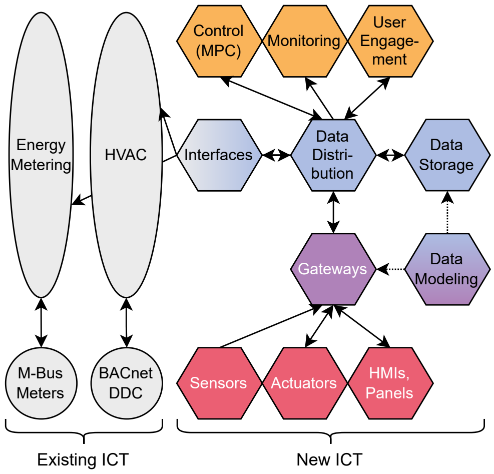


Fig. 3 Overview of the methodology for integrating existing and implementing new ICT components.

3.1 Integration of Existing ICT Components

Making live metering data available for research purposes depends on integrating existing ICT infrastructures. Once access is granted, a lot of information is available for evaluation. This allows for analyzing infrastructures, assessing technologies, and automating the detection of sub-optimal operation and energy wastage.

3.1.1 Building Energy Metering

As outlined in Section 2.2.1, energy demands are recorded through the campus-wide metering system. We integrate this system into our ICT setup to provision of real-time energy consumption data to all staff members via a web-application. The integration is done by interfacing the proprietary data acquisition software of the metering system via an add-on, Figure 4. The add-on enables the transmission of live data via MQTT

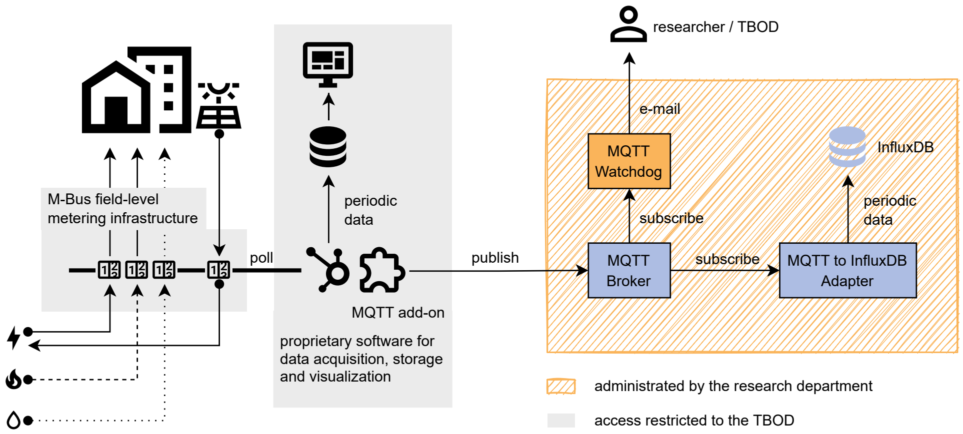


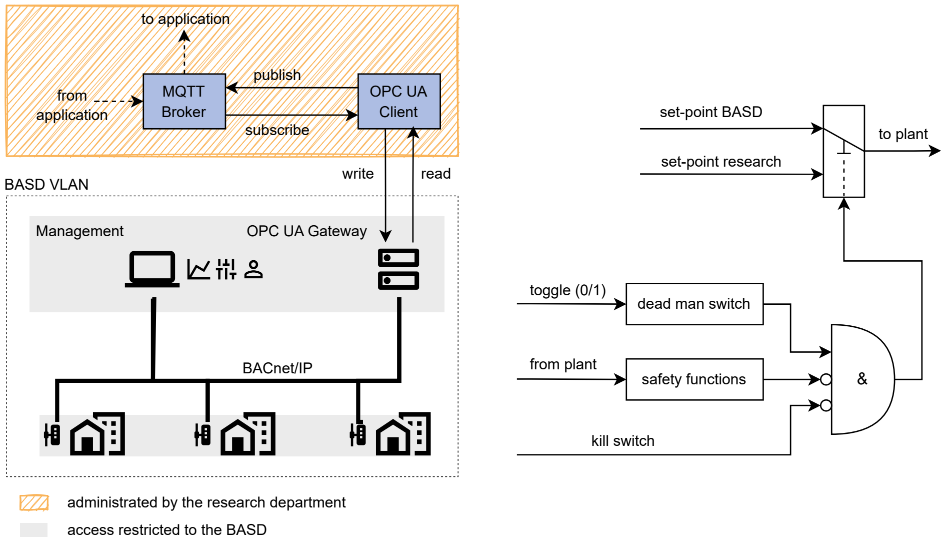
Fig. 4 Integration of the existing energy metering infrastructure into the proposed ICT setup through an MQTT interface.

and is configured to forward data regularly, e.g., every minute. A mapping configuration file is used to assign MQTT topics to the individual metering data points. To generate the configuration file, a parsing tool has been developed to extract metadata on the data points from their individual tags. The tags base on a standardized tagging schema. The tag of a data point includes all basic metadata, such as the location of the meter or measured quantity and has a unique identifier. The parsing tool processes the unique identifier and the tag to generate a topic for each data point based on the metadata. These topics are then used for publishing the live data on an MQTT broker. Finally, an adapter script, subscribed to the same topics, stores the data in an InfluxDB [92] database. InfluxDB was chosen for its superior performance for time-series data and flexibility. Network traffic is protected by TLS encryption and user authorization. To monitor interruptions in data transmission, an MQTT watchdog has been developed. The watchdog notifies administrators via e-mail of missing MQTT messages on certain topics. It can also be used to detect limit violations by evaluating the payloads of individual MQTT topics. This enables rapid repair initiation and automated incident reporting to users and maintainers.

3.1.2 Building HVAC

The site-wide HVAC monitoring and control platform, operated by the BASD (Section 2.2.2), features a central HVAC management for all buildings of the site. Through the central HVAC management, the BASD configures building-wide HVAC set-points, e.g., heating curves. Being able to influence the buildings' heating-curves, has two main advantages [93–96]: On the one hand, the feed temperature can be flexibly adjusted to varying demands, leading to lower average feed temperatures and decreased thermal losses. On the other hand, the operation of new room-level heating controllers can be synchronized with the supply control at building-level, avoiding, e.g., comfort losses due to misaligned heating-curves.

Allowing researchers direct access to the BACnet/IP infrastructure from outside the isolated network would introduce unnecessary security vulnerabilities and is potentially error prone. Therefore, the OPC UA [97] protocol is used to provide access to specific data points and field devices in the BACnet system. Commercial gateway software to translate between the two standards is put in provided by the BASD, see Figure 5a. The software represents BACnet data objects as a hierarchical node structure on the OPC UA server. The research department's write action to the OPC UA nodes is propagated to the corresponding data object in BACnet. A change of value



(a) (b)

Fig. 5 In (a), extension of the existing BACnet setup by an OPC UA server; in (b), handling of multiple sources of set-points.

in BACnet, e.g., a measurement by a sensor, is forwarded to the research department as a change of value at the corresponding OPC UA node. The data can be retrieved from the OPC UA node, e.g., through a request or a change-of-value notification. The gateway software is deployed inside the BASD VLAN. The only permitted connection to the OPC UA server is through an OPC UA client from the research department using a previously configured port. The client machine can read, write, or subscribe to the data points on a white-list of OPC UA nodes. Finally, two-way data transmission between the client and an MQTT broker is established.

Additional logic is needed to distinguish between set-points of the BASD and those of the researchers to ensure smooth operation. The operation mode switch is implemented on the local DDC device using BACnet automation. The decision of which set-point is forwarded to the plant is based on a combination of functions, Figure 5b. The BASD can enable or disable the research department's set-point via a kill-switch through the HVAC management's web interface. This feature can be useful during maintenance work on the plant. If a safety-relevant function like a fire detection system is triggered, the system automatically switches back to default operation. A dead man switch has been implemented. The research department toggles a bit within a predefined time-frame (heartbeat). If it fails to continue, the system switches back to default operation. This measure increases the overall reliability and allows the research department to prevent falling back to BASD operation mode if identical set-points are provided for an extended period of time, e.g., on weekends or during nighttime. The implemented kill-switch thus automates switching between the established DDC-based BASD control (i.e., heat curves that depend on ambient temperature and time of day) and novel experimental control algorithms.

3.2 Implementation of the New ICT Components

In the following sections, we describe the software components and their interconnections with each other as well as their interfaces to the underlying communication infrastructure. We strongly pursue IoT-readiness through the consideration of the basic IoT principles (Section 2.3) for our software prototypes to anticipate the expected needs for scalability, e.g., when including more buildings or integrating other energy system components in the future.

3.2.1 Device Identification Procedure

Published in [36], field-level sensors and actuators have been retrofitted in several buildings. Based on the buildings' prerequisites, two different technologies had been selected. First, a primarily wired KNX [98] bus infrastructure for energy-intensive devices (e.g., control panels) and those that interface with existing electrical or building automation infrastructure (e.g., occupancy sensors, light switches, blinds). Second, standalone, radio-based EnOcean [99] sensors and actuators, that allow for a less intrusive retrofit of rather isolated functionality (e.g., contact sensors, radiator valve actuators). Both technologies work quite differently. EnOcean is based on *EnOcean Equipment Profiles* (EEPs), which define the structure and contents of radio telegrams emitted or received by EnOcean devices. Each device implements one or multiple EEPs, but during commissioning, one EEP must be selected. The selected EEP defines all available features and functions of the device. Contrarily, in a KNX installation, devices provide so-called *communication objects*, depending on the device's features (e.g., on/off for a switch). Communication objects can be linked across multiple devices (e.g., light switch and light actuator) through *group addresses* by programming the devices to listen to or write bus telegrams via a certain group address. Thus, the desired automation functionality in KNX is indirectly defined through the communication objects within a group address.

To identify all available data points for room-level monitoring and control, information about the deployed devices must be made available to both applications and users. This includes the device type (i.e. the implemented functionality), the device location, and any other metadata required to integrate the device into the ICT/IoT infrastructure. Due to the different nature of EnOcean and KNX, we choose two separate approaches to access the heterogeneous data sources while maintaining a single point of truth for each technology.

In the case of KNX, the current building automation constitutes the single point of truth as it encompasses the commissioned devices, their parametrization and programmed group addresses. The current automation, however, is not explicitly available as it is spread among the devices. The assignment of group addresses is done via the *KNX Engineering Tool Software* (KNX ETS). The KNX ETS uses an XML-based project file to represent the bus architecture, its devices and the communication between them. This project file is therefore the main source of information that, if carefully maintained, will accurately represent the current automation.

At FZJ, the KNX system configuration is handled by the TBOD. To manage the revisions of the KNX ETS projects, we establish a version control workflow built on a shared Gitlab [100] repository, Figure 6. Both the TBOD and the research depart-

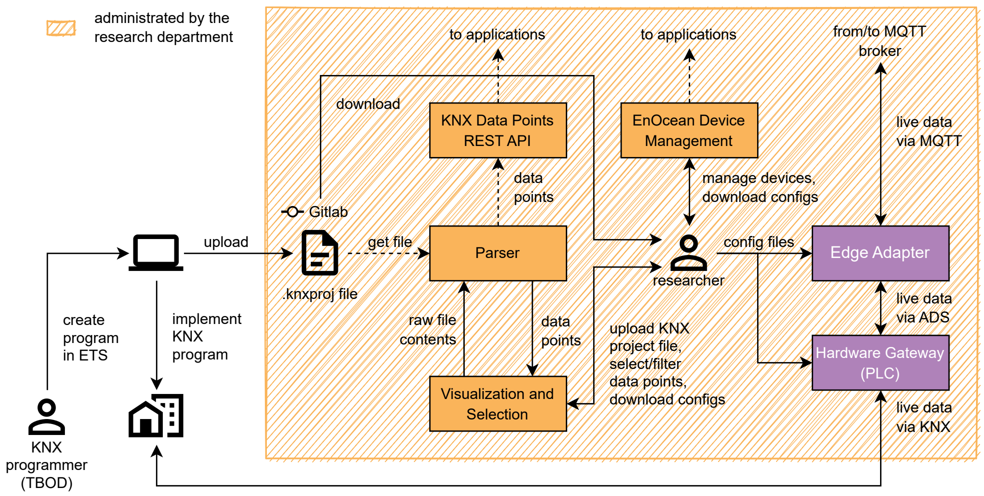


Fig. 6 Management and identification of data points for field-level devices using KNX and EnOcean.

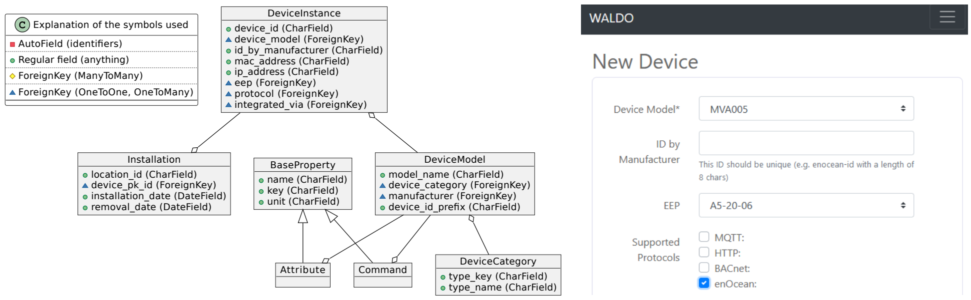
ment have access to the repository, which enables programmatic on-demand access to the project file through the Gitlab API. To interpret the program, we implement a parsing module (based on the open-source package *xknxproj* [101]) that extracts information on the group addresses (i.e., the data points). The parser module can also extract additional metadata from the group address name field (specified by the KNX programmer) using regular expressions. Parsing metadata from free text fields makes consistent naming of data points very important and partly a requirement; not following the required naming scheme can result in loss of information, and adapting the regular expressions to naming inconsistencies is a tedious task; however, to the best of the authors' knowledge, this is the only applicable way to store, e.g, site-specific location or function-related context in KNX. Finally, the parser is employed to expose the data points via a REST-API built with FastAPI [102] and visualize the data points through a Python-based web-application. The web-application can also be used to select data points for creating and downloading configuration files for gateways or edge adapters, which together form the link between the operational technologies and the data distribution layer (see Table 1).

In the case of EnOcean, the physical devices are installed, commissioned and maintained by the research department. Therefore, we introduce a dedicated device management tool to manage EnOcean devices (see Section 3.2.2), since to the best of the authors' knowledge, such a tool is not available. The EnOcean device management tool comes with a separate REST-API that, similar to the KNX data points API, can be queried to get information about the available data points implemented by the EnOcean devices. This information can be used to generate configuration files for both gateways and edge adapters (see Section 3.2.3).

3.2.2 Management of Physical Devices

The introduction of many EnOcean devices requires faster and automated device commissioning and connection to ICT infrastructure. Tracking the location and technical parameters of installed devices is also vital for applications like room-individual controllers for heating. To address this, we present WALDO (Web Application for Device Organization), a central device management tool that currently handles over 4,000 sensors, actuators, and gateways. WALDO allows for the storage of static and variable information for each device.

WALDO is a Django-powered [103] application based on an SQLite [104] database. User account data is stored in the database as well as the device data. The relational database model, Figure 7a, harmonizes device information and avoids storing redundant information. Authorized users can interact with WALDO through a web interface or its REST-API. The web interface provides several forms to enter or modify device data and a tabular that displays all or a filtered list of specific devices, Figure 7b. The list of selected devices can be exported to a CSV file. To add a device to WALDO,



(a) (b)

Fig. 7 In (a), Unified Modeling Language (UML) diagram of a device database model; in (b), screenshot of the WALDO user interface.

a form is filled with device-specific information such as a vendor identifier, supported protocols or EEP used by the device. For convenience, values of non-unique fields can be auto-populated based on the device type. Finally, the entered data is validated before the device is stored in the database.

For programmatic data retrieval, the REST-API of WALDO provides an endpoint to request lists of devices in JSON [105] format. Server-side filtering by building, wing, room, or device ID is possible. Thus, the API can be used to check for devices installed in a specific building space or to resolve the metadata for a given device. When a new device is created, a unique device ID is generated. This ID is used to identify the device and to label the physical device. It is therefore descriptive[1]. Although there are several methods for naming data points in the context of building automation, e.g. the BUDO schema [106], we use a rather simple naming scheme. This is reasonable because device metadata can be easily obtained by querying the previously described endpoints.

[1]The ID is constructed from the device type ("G" for a gateway, "S" for a sensor, "A" for an actuator, "H" for a human machine interface or control panel), a key for the quantities measured or controlled (e.g., "CHT" for the measurement of CO_2 concentration, humidity and temperature), and an auto-incrementing positive number (e.g., "123"). An air multisensor, hence, could have an identifier like `S_CHT_123`.

3.2.3 Data Models

Using different devices and protocols at the field level leads to in-homogeneous metadata because the source, structure, and format of available information differ. This poses two challenges: collecting data from gateways requires adapters to understand the data structure, and unifying data to enable dependent applications to request data without further context. To address these challenges, we define data models for all available devices or data points. Each model consists of the following items:

- `id`: A field for a unique identifier, e.g., the device ID generated and assigned in WALDO or a hash-based ID for KNX data points, derived from the group address name.
- `type`: The name of the device or data point type, i.e, the name of the device model implementation on the gateway.
- `attributes`: A list of attributes, i.e., read-only variables. This list contains all measurements that the field-level devices obtain as well as attributes that exist as device-related parameters on the gateway, e.g., unit conversions or offsets.
- `commands`: A list of commands, i.e., write-only variables. This list contains the all commands that the field-level device provides as well as additional commands implemented on the gateway, e.g., mode selectors for control algorithms or state machines.

The ID enables any application, including the edge adapter, to unambiguously identify a device. This holds for both live-data and device metadata. With the type information, data models can be assigned to a device through a simple mapping between ID and type. This allows linking multiple devices to one data model, which facilitates resolving attributes and commands of a device. We implement the data models in YAML [107] and their counterparts on the gateways with type and class objects of the gateways' programming language (see Section 3.2.4).

3.2.4 Field-data Collection and Storage

Our ICT setup connects field-level devices in real time. Different bus protocols require a gateway to connect them to the data distribution layer, and we use programmable logic controllers (PLCs)[2] for that task. In the case of EnOcean devices, we use a wired CAN bus [108] backbone with multiple EnOcean transceivers that connect to the devices by radio. In the case of KNX devices, the bus topology consists mainly of wired devices with only a few radio-based (KNX-RF) devices, which are integrated into the wired KNX system via dedicated KNX-RF bridges. In both cases, the PLC interfaces the backbone lines of the busses, see Figure 8. On the PLCs, we link inputs

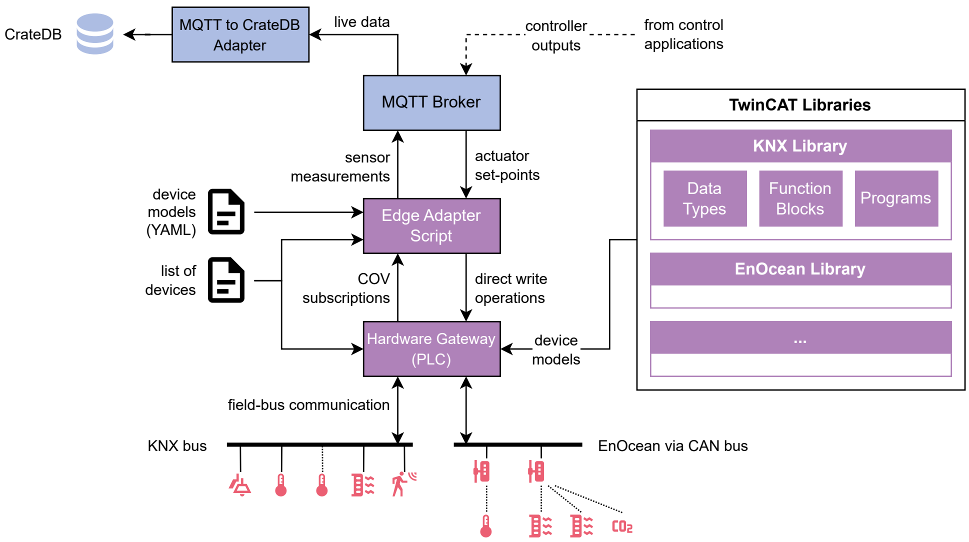


Fig. 8 Collection and harmonization of data from/to field-level devices via PLCs as gateways.

and outputs of the bus interfaces to buffer variables and interpret them using the vendor's communication libraries. We then use custom PLC libraries to handle the

[2] CX5130 Embedded PC from Beckhoff Automation LLC

data points on the PLCs. In these libraries, we assemble the device data models using *function blocks* (FBs) and custom *data unit types* (DUTs), which are the class and type equivalents in the TwinCAT 3 [109] programming language. We also bundle logical functionality, interpretation of field-bus communication (i.e. writing commands via the buffer variables) and basic control logic in the device-specific FBs. This object-oriented approach allows sustainable development and deployment of programs for multiple PLCs (i.e., for multiple buildings) with a comparatively low implementation effort.

We establish live-data transmission from the PLCs to our distribution infrastructure by feeding the edge adapters with the data models implemented in YAML and a mapping to the respective FBs. In addition, both the PLCs and the adapters are configured with a list of devices. This allows the adapter script to locate the device instances (i.e., the FBs) on the PLC through the device IDs and resolve all related attribute and command variables using the device type information. The edge adapter uses the *pyads* [110] package to access the respective variables on the PLC. Read operations are implemented using change-of-value (COV) notifications. Device data, i.e., attribute values, are transmitted from the PLC to the script on change. Write operations are performed directly on the PLC variables, i.e., the device commands. Northbound data traffic from the adapter is handled via MQTT. Any change of device data is published by the edge adapter to an MQTT broker using a topic structure based on the ID and type of the device. The message payload is a dictionary with the attribute or command name(s) and the respective value(s). By subscribing to the MQTT broker, data is retrieved by a database adapter script that inserts it into a CrateDB [111] time-series database. A CrateDB was chosen because it provides good performance for time-series data, supports structured values (i.e., JSON), and scales well horizontally. To send commands to be applied to the devices, control applications can publish messages directly to the broker via the appropriate topics. The edge adapter subscribes to all command-related topics of the devices in its configuration and is thus able to map and write the incoming command to the correct variable on the PLC.

3.2.5 Data Visualization, Analysis and Pre-processing

Once device data is collected via the ICT infrastructure, it can be used by monitoring, control, and user-engagement-related applications. However, it is advisable to be able to visualize and analyze the data beforehand. For the plain visualization of data, we use the open-source solution Grafana [112]. Grafana accesses databases directly and periodically retrieves data via user-defined Structured Query Language (SQL) statements. In Grafana, we aggregate, e.g., building-level metering data from the InfluxDB and room-level device data from the CrateDB to advanced dashboards for buildings or rooms that are controlled. On the other hand, the growing amount of data requires new tools to monitor building performance and prepare data for scientific use. Monitoring and scientific evaluation of data depend on high-quality data, so identifying outliers, device failures, and lost connections is critical. We developed a Python toolbox to pre-process and analyze data in this regard. A detailed description of the toolbox features can be found in [113]. Nevertheless, we will briefly discuss the detection of outliers here, as this is essential in real-world scenarios. Figure 9 shows an example of the outlier detection algorithm applied to two time-series (temperature and CO_2 concentration measured in a room) with a varying time resolution of 15 to 30 minutes. In this example, the difference-rule[3] was applied to the temperature time-series. The difference-rule was chosen for the time-series because air temperature typically changes slowly over short periods. The threshold of the difference-rule was calculated with the help of the one-sided σ-rule, where in this case $k = 2$ has proven as robust[4]. For the CO_2 time-series, a rule that is not sensitive to fast changes must be used, because the CO_2 concentration of a room can change very quickly within a

[3]The difference-rule calculates the difference $d_i = |y_i - y_{i+1}|$ between each pair of consecutive data points. If a difference d_i is greater than a specified threshold c, an outlier (d_{i+1}) is found.

[4]The one-sided σ-rule implements a threshold by $c = \bar{d}_i + k\sigma_{d_i}$, where $\bar{d}_i$ is the mean and σ_{d_i} the standard deviation of the differences, and k is a scaling factor.

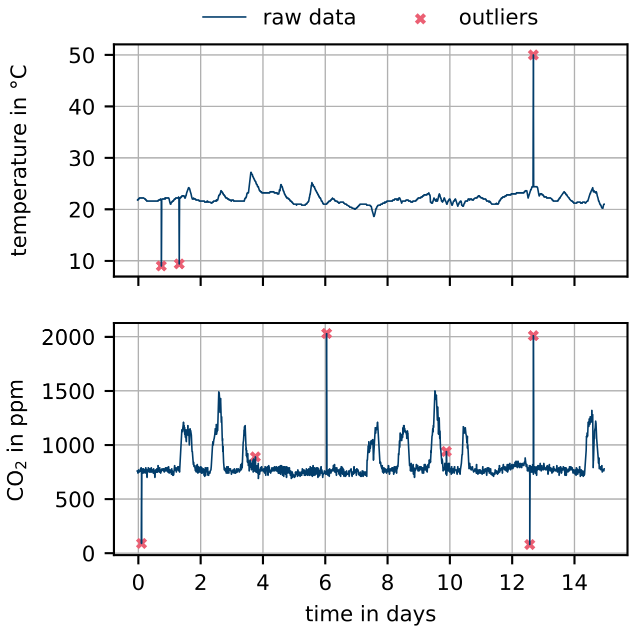


Fig. 9 Example of the detection and handling of outliers in time-series data.

few minutes. Therefore, the local σ-rule[5] was applied with a window width, i.e. the number of data points in the window, of 21 and $k = 3$, both of which proved to be robust parameters.

3.2.6 User Engagement: The Energy Dashboard Suite

The *Energy Dashboard Suite* [114] contains user-focused software applications for the visualization of energy-related information for various stakeholders (e.g., building occupants, facility managers, building operators, or researchers), room automation, and the evaluation of energy efficiency. Through this suite of applications, which is available to staff members of FZJ, users are integrated into the energy ecosystem of the campus with possibilities to view the status of the energy system, and to influence it. The first component, the *Dashboard*, visualizes the energy consumption at building

[5] The local σ-rule uses a sliding window with a predefined width. The window is shifted over the entire time-series to test whether the central data point of each window is not in $[\mu_i - k\sigma_i; \mu_i + k\sigma_i]$, where μ_i is the mean and σ_i is the standard deviation of the data points in the window, and k is a scaling factor.

level and for the entire campus for heating and electricity in real-time. A time-limited historical view of the data is also available. Additionally, it enables the visual comparison of building demands in a map interface, as shown in Figure 10. Furthermore, the energy production time-series for buildings with PV installations are shown on the respective building pages. The demand data shown on the Dashboard is derived from the building-level metering data gathered by the metering system of the TBOD (see Section 3.1.1). The second component of the Energy Dashboard Suite is *JuControl*,

Fig. 10 Screenshot of the Dashboard showing the comparison view for building heating demand.

which shows data at room level, including indoor environmental quality measurements (CO_2 concentration, humidity, room temperature, luminosity) and the status of the heating system (valve position and temperature set-point of the radiator(s)). Furthermore, a pseudo-3D view of the room is shown in JuControl, indicating the status of the windows and doors (open, closed, or tilted, as applicable) in real-time. The 3D view is created through direct specification of the room geometry and main features in a mini-language called *ALICE* [115]. The room components (windows, doors, radiators, etc.)

are then enriched with sensors via processing of the device data stored in WALDO. For this step, ALICE requests the device data from WALDO via its REST-API, and then processes the device characteristics to determine which rooms and room components the devices belong to. The sensor data visible in JuControl comes from the CrateDB.

In addition to the visualization capabilities of JuControl, users can also use automatic heater control by providing schedules of their expected presence in the office, along with a comfort temperature range to serve as set-point for the room-level heating system, which in most cases includes high-temperature hydronic radiators [116]. This data is exposed by JuControl to the rest of the ICT framework via a REST-API that produces a time-series of aggregated presence and temperature preferences for the occupants of the room for future time-steps. Using this data, the heating controller can make control decisions about the heating system. Additionally, occupants can temporarily override the default set-points derived from their schedule, for example when their presence differs from the schedule due to an impromptu event, by directly specifying a temperature set-point in JuControl (see Section 3.2.7).

Finally, JuControl is equipped with a gamification part that is powered by a tool called *Juracle*, which evaluates the thermal energy efficiency of offices considering occupants' window ventilation patterns and set-point temperatures. This gamification system has the ability to provide real-time recommendations to occupants, as well as detailed energy ratings and rankings compared to other offices. Since the purpose of Juracle is gamification, its evaluation strategy is designed to target particular aspects of occupant behavior related to energy efficiency. For further information the reader is referred to Ubachukwu et al. [114, 116], which discuss design, implementation, and evaluation of the Energy Dashboard Suite's components in detail.

3.2.7 Management of User Inputs

Users can interact with the controlled system in several ways. An evaluation must therefore take place to convert multiple input sources to a single input for the intelligent controller. This allows for reliable and transparent control behavior considering user preferences [117]. In the case of space heating within the LLEC, the following input paths are available to the occupants: First, manual interaction with the local radiator valve actuator to increment or decrement the temperature set-point by ±1 °C within the range of 21 °C±5 °C. Second, adjustment via a HMI installed in the room. Third, interaction through a web-interface as part of JuControl (see Section 3.2.6). Through the web-interface of JuControl, users can specify either a single temperature set-point or a daily schedule including upper and lower temperature bounds.

Schedules can be easily integrated into an MPC to unlock energy-efficient room control, but any other user inputs must also be considered. To address this, we have developed an algorithm, Figure 11, that handles user inputs in the following way: Room operation based on a user-defined schedule is activated by default, unless there's been direct user interaction (e.g., setting a set-point in JuControl) within the last eight hours. If no schedule is configured, we apply a standard one. Local interactions are applied immediately. If multiple interactions are observed, the last one takes precedence. The selection algorithm retrieves active schedules and temperature set-points from the REST-API of JuControl. It also interfaces with the CrateDB database to detect local interactions. From the database, it collects time-series data from HMIs and radiator valve actuators to identify local set-point overrides. It then selects one active source of user input and communicates the decision via the database to JuControl for visualization and user feedback. Finally, the set-point information is supplied to the controller, which calculates the control commands (e.g., a valve opening value) to be sent to the devices. Once the control commands are calculated, they are implemented via the southbound ICT infrastructure via the MQTT broker, as described

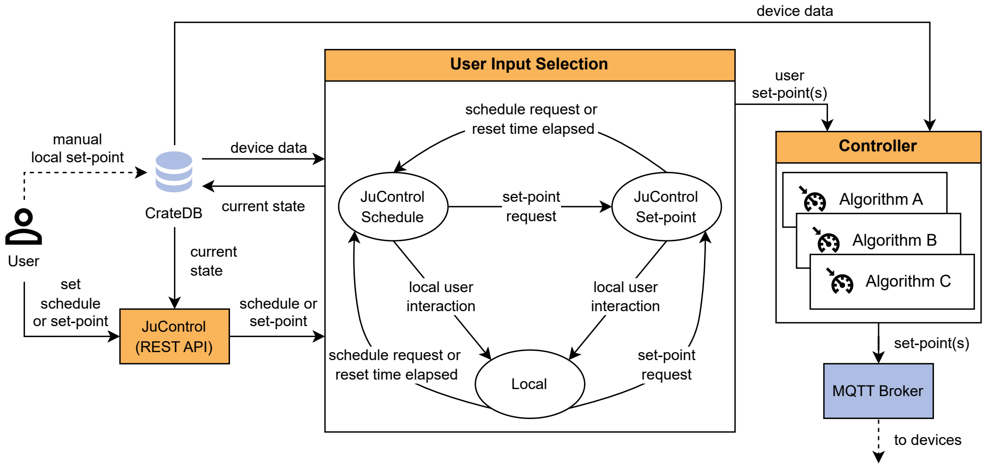


Fig. 11 User input selection mechanism to determine the active temperature set-point source for room-level heating control.

in Section 3.2.4. The controller element is replaceable, facilitating the application and evaluation of different control algorithms. For a detailed description of the selection algorithm, please refer to Althaus et al. [117].

3.2.8 Control Applications

We aim to seamlessly integrate intelligent controllers into the ICT infrastructure to evaluate them in the real world. To ease the application of controllers, we have implemented plug-and-play communication, forecast modules, and interfaces to databases that can easily be integrated into control frameworks. The structure of an exemplary framework for MPC is shown in Figure 12. MPC depends on forecasts of energy supply and demand. To predict thermal building loads, we have implemented a tool that collects booking data for shared spaces from a self-hosted Microsoft Exchange Server [118], stores this data in a PostgreSQL [119] database, anonymizes it, and makes it available via a REST-API. This information, combined with historic measurements (i.e., the number of occupants for a past event obtained from the CrateDB), improves the forecast accuracy of internal energy gains. Weather forecasts are obtained through

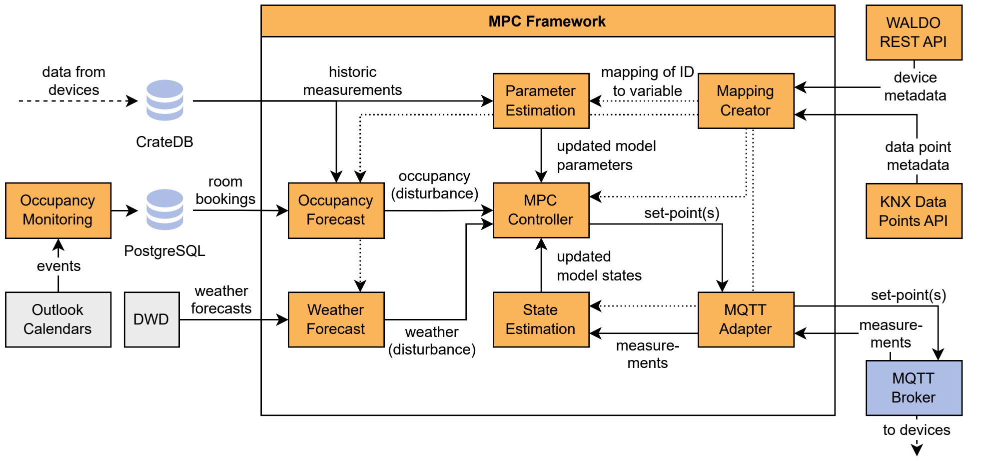


Fig. 12 Exemplary control application employing an MPC framework for optimal control of HVAC systems in buildings.

the Python package *wetterdienst* [120], which retrieves forecasts from open weather data providers. Other Historic measurements, e.g., for parameter estimation, can be fetched from the databases via database adapters. To resolve device and data point metadata, the MPC framework consults the respective REST-APIs of WALDO or the KNX counterpart. This enables the allocation of historic device data to MPC parameters and the communication of control set-points via the correct MQTT topics. Finally, live measurements from the controlled system can be incorporated directly via subscribing to the respective MQTT streams. Note that the design of an MPC itself is not the focus of this work and is therefore not discussed here. For more details on controllers that we embed into our ICT suite, the reader is referred to Mork et al. [121] and Althaus et al. [117].

3.3 Network Architecture and Security

The IoT devices used take remote commands to adjust their operation. Since they often collect sensitive data, it is crucial to protect them from possible cyber attacks. Many IoT devices have limited processing power and storage leading to weak security features or making them prone to denial-of-service attacks. One measure to protect IoT devices on the network level is by placing them into Virtual Local Area Networks (VLANs) [122]. Using VLANs, network administrators can limit the network traffic visible to and interacting with the IoT devices. Besides, administrators can restrict the number of devices and users able to interact with the IoT devices on the network, improve the monitoring of devices, and enforce access control policies. For our setup, we use several VLANs for different device groups, similar to the existing VLANs for building energy metering (Section 2.2.1) or HVAC management (Section 2.2.2) and allow access through their respective network gateways only. With respect to data transmission, REST-API access, and interfaces between the mentioned services and applications we use state-of-the art SSL/TLS encryption and (certificate-based) authentication. In the case of the Energy Dashboard Suite, we enable login based on the on-site identity provider of FZJ.

3.4 Software Development and Deployment

The new ICT components extend the capabilities of the existing building automation setup and introduce new operational features such as room-level heating control. This places new demands on the research software components in terms of availability, performance, and reliability on the part of the various stakeholders. To meet these requirements, we have aligned our activities to the core practices of DevOps (Development and Operations): Continuous Integration (CI), Continuous Delivery and Deployment (CD), and Infrastructure as Code (IaC) [123]. To centralize the code and make changes back-traceable, we employ Gitlab as source code manager. This allows us to work on code collaboratively and properly release different versions of application code. In addition, Gitlab offers built-in CI/CD features (e.g., Gitlab CI/CD pipelines), which we use to create Docker [124] images of our applications, automatically generate code documentation, and run software unit-tests. If required, e.g., in the case of the Energy Dashboard Suite, we also use dedicated deployment environments for production and development state, respectively, to perform end-to-end tests or gather user feedback on a pre-release version of the application. Regarding IaC, we build upon OpenStack [125] to manage virtual computing resources and configure the servers. Software deployments and images of databases, brokers, and custom software are managed through GitLab. Finally, we use the container orchestrator Portainer [126] to handle all containerized components. This DevOps-driven approach enables us to deliver software solutions that are tested and stable, documented, and, finally, can be developed and deployed in a standardized, comprehensible way.

4 Results and Discussion

In this chapter, we present the results of our work. First, we outline the complete ICT setup. Then, we assess our ICT setup with respect to the functional requirements identified in Section 2.4 and evaluate it based on key performance indicators (KPI). Finally, we showcase the results of an exemplary real-world use case in which we apply an MPC by means of our ICT setup.

4.1 Summary of the Resulting ICT Setup

We structure the resulting ICT setup, Figure 13, based on the IoT reference architecture as established in Section 2.3. In the *Operational Technology* layer, the ICT comprise the energy metering components which are administrated by the TBOD, the HVAC units operated by the BASD, and the devices we deployed to the buildings for monitoring and control. The *Edge* layer of our ICT setup includes building-individual gateways in the form of PLCs and edge adapters that handle the bi-directional streaming of measurements and set-points to/from the data distribution layer. The *Data Distribution* consists of MQTT brokers to flexibly connect edge and application level components, and multiple cloud-hosted databases to persist device data. Finally, the

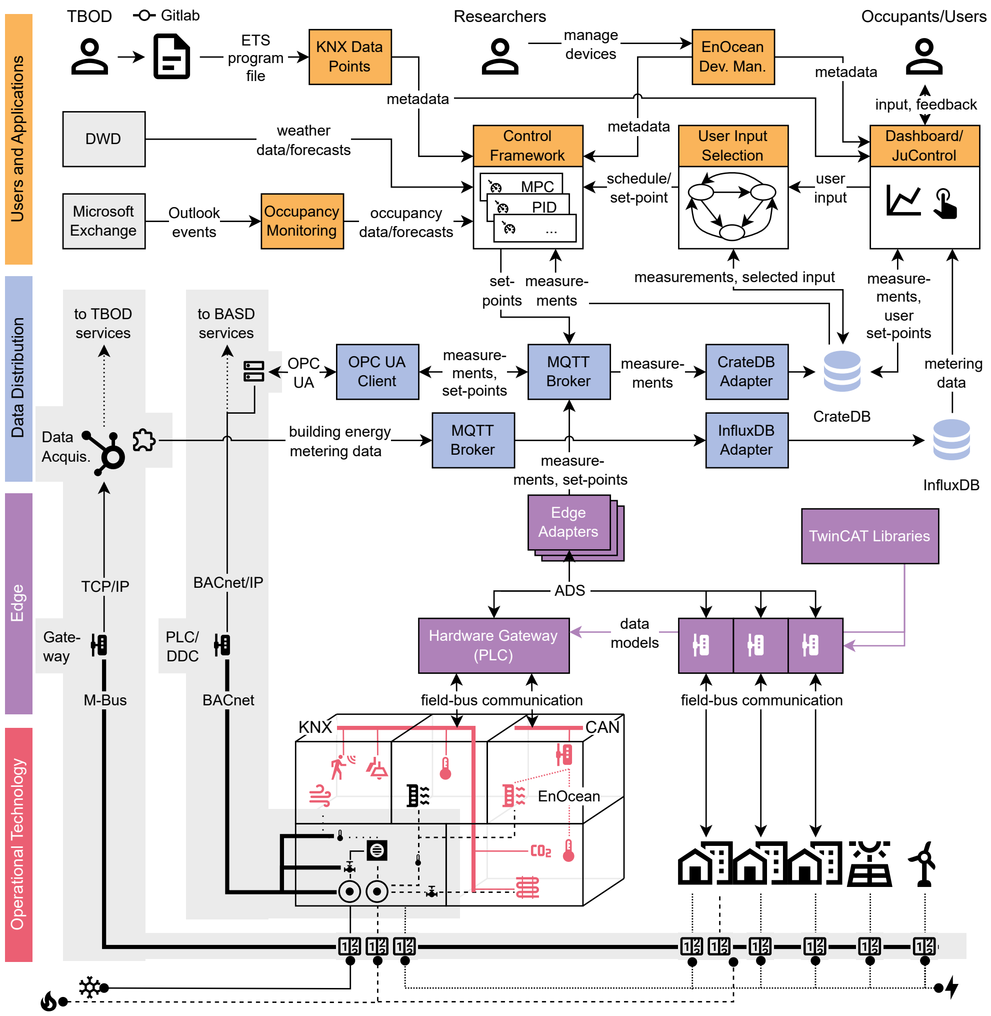


Fig. 13 Resulting complete ICT setup based on the reference architecture in Section 2.3 and the components presented in Section 3.2.

Users and Applications layer includes the applications we have developed as part of our living lab approach for both research and management purposes. They follow IoT principles and exchange data with other ICT components via REST-APIs, brokers and databases.

4.2 Functional Evaluation

This section provides a discussion of the implemented functionality with respect to the requirements derived in Section 2.4. A summary of the evaluation is provided in the form of a rating through Table 2. The advantages, disadvantages, and lessons learned per ICT component are listed in Table 3, Table 4, Table 5, Table 6, and will be discussed in more detail in Section 4.2.1 and Section 4.2.2.

4.2.1 Integrated Existing ICT Components

The integration of the existing building energy metering infrastructure provides standardized live data for research, as well as aggregated electricity and heating energy consumptions per building or wing. The interface's simple configuration enables flexible data transmission. However, the data transmission rate is limited, measurements are not automatically synchronized, and access to historical data is still constrained. Nevertheless, metering data can provide valuable insights into building energy usage, such as current heating operation modes and conclusions about the building envelope's thermal properties [93]. Interfacing the existing building HVAC management system had been challenging because it involves technical and reliability-related aspects. The solution based on OPC UA integrates BACnet functionality seamlessly while strictly limiting controllable properties. This is a major improvement because it allows the inclusion of HVAC components into the control setup, increasing control effectiveness. Lastly, the kill-switch guarantees reliable operation.

4.2.2 New ICT Components

Retrofitted sensors and actuators at room-level unlocked energy monitoring and enable user-centered heating control. The selected technologies fit various building styles, meet reliability demands, and promote scalability. The large number of devices, however, requires proper management and installation and maintenance. Therefore, it is

Table 2 Evaluation of the ICT components; "x"/"o" for full/partial fulfillment of the requirements.

Layers	Users and Applications						Data Distribution			Edge		Op. Tech.	
Requirements	Device Management	Collection of User Preferences	Provision of Feedback	Monitoring	Analysis	Control	Data Accessibility	Data Distribution	Data Storage	Data Collection	Data Harmonization	Measurement	Control
Integrated Ex. ICT	Level of Attainment												
Energy Metering							o	o	o			x	
HVAC							o	o	o			x	o
New ICT	Level of Attainment												
Additional Devices at Room-level												x	x
Device Identification Procedure							x	x	o				
Management of Physical Devices	x						x	x	x				
Data Models											x		
Field-data Collection and Storage							o	o	x	x			
Data Visual., Analysis and Pre-processing				x	x								
User Engagement		x	x	x	x								
Management of User Inputs						x							
Control Applications						x							
Overall	x	x	x	x	x	x	x	o	o	o	x	x	x

important to keep the set of different device types small to reduce familiarization times and costs.

In terms of device identification and management, the proposed ICT components are able to store, provide and distribute device metadata. A single point of truth for device metadata is established for both KNX and EnOcean devices. In addition, information about a device can be requested by either applications or edge components via REST-APIs. However, a major drawback of this approach is that metadata must be requested from two (or in the worst case, many) different sources, which limits the scalability of the whole setup. To overcome this, a single access point to metadata should be introduced in the future. Such an ICT component should be able to manage both entities with physical counterparts and those that exist only for semantic linking.

The introduced data models standardize the nomenclature for device attributes and commands, enabling data harmonization. These models generalize attributes and commands across protocols and manufacturers. Stored data can be obtained by type, identifier, attribute name, or command name. This abstraction layer enables applications to discover and use correct data points easily.

Table 3 Advantages, disadvantages, and lessons learned for the integrated existing ICT components.

Component	Advantages	Disadvantages	Lessons Learned
Energy Metering, Section 3.1.1	• standardized live data • high availability/coverage • lightweight interface • clear separation of systems	• no long-term historical data • limited throughput	• useful for consumption overviews and fault detection • not useful for grid analysis • if feasible, integrate energy meters directly
HVAC, Section 3.1.2	• unlocks building-wide HVAC control • new insights into building-wide automation	• cumbersome integration (BACnet/OPC UA)	• kill-switch required for system separation • discuss control interaction with TBOD/BASD as early as possible

The new PLC-based gateways connect field-level devices to the cloud flexibly and scalably. They are also able to implement fallback control logics, increasing reliability. The MQTT and time-series database data collection and storage setup provides a simple yet powerful infrastructure that connects to the gateways through adapter scripts. This setup is flexible but costly to configure and implement. Programmable gateways require expertise in PLCs, hardware, and programming languages, which can hinder research readiness. Data models must be translated to the PLC, which can be cumbersome and prone to errors when models change. Nonetheless, programmable gateways have clear advantages: broad compatibility, versatility, and reliability, which are essential in research environments.

Table 4 Advantages, disadvantages, and lessons learned for the new ICT components (part 1/3).

Component	Advantages	Disadvantages	Lessons Learned
Additional Devices at Room-level, [36]	• unlocks room control • additional insights on energy use	• device management required • commissioning effort	• assess individual building prerequisites • use a small set of device types
Device Identification Procedure, Section 3.2.1	• single point of truth per protocol • standardized access to device metadata	• no virtual device representations	• identification procedure depends on device technology • favor technologies that come with machine-readable specifications
Management of Physical Devices, Section 3.2.2	• easy management of device metadata • standardized REST-API	• limited to retrofitted devices • only applicable to physical devices	• fundamental to keep track of devices/installations • importance increases with the number of devices
Data Models, Section 3.2.3	• enables data harmonization across technologies and protocols	• implementation effort depends on the number of device types	• prefer models that can be easily extended • simple device identifiers are sufficient if metadata is accessible via endpoints

We augment the ICT setup with data visualization and analysis tools for continuous building monitoring and ad hoc energy consumption analyses. While Grafana is

Table 5 Advantages, disadvantages, and lessons learned for the new ICT components (part 2/3).

Component	Advantages	Disadvantages	Lessons Learned
Field-data Collection and Storage, Section 3.2.4	• scalable and extendable • allows for edge programming • lightweight interfaces through micro-services • comprehensive time-series storage	• PLC programming requires expert knowledge • additional data modeling, abstraction layer	• define models in a generalized form to be able to use them in different contexts (PLCs, edge adapters, etc.)
Data Visualization, Analysis, Pre-processing, Section 3.2.5	• visualizations for different stakeholders • automated fault detection and operation analysis	• limited live-analytics features	• analytics features gain importance with increasing device counts
User Engagement, Section 3.2.6	• energy flows become visible for users • direct feedback on energy consumption • enables gamification	• effort of software maintenance and (technical) support • failures affect user comfort and acceptance	• establish development and operations (DevOps) workflows • introduce software specialists • involve users in the design process

a flexible solution for building monitoring dashboards, our Python analysis toolbox can be integrated into fault-detection and analysis tool-chains. The Energy Dashboard Suite is used to conduct user engagement research. It provides all the necessary functionality to collect user preferences, provide feedback and transparently communicate energy consumption. The suite is well integrated with the other ICT components through REST-APIs and builds on the established MQTT data distribution infrastructure. As it is the main interface for users to control their individual room heating set-points, high service availability is required. As a result, the software and its lifecycle must be carefully managed, making sophisticated DevOps standards essential. This can lead to additional costs for personnel, training and resources. Besides user engagement, building operation and control is the main research topic for which the presented ICT setup has been developed. Since users can specify set-points in more than one way, an overarching management of user inputs is developed that collects preferences from multiple sources and combines them into a single set-point. This set-point can then be used in the control application. As a result, set-points can be safely and reliably distinguished, and time-dependent schedules and fallback plans can be supported. Despite the additional cost of managing multiple sources, the user input management takes into account the different ways in which users prefer to provide set-points and the heterogeneity of input options available in buildings. The mechanism developed allows for consistent and understandable operation and can be combined with any type of controller, from relatively simple rule-based ones to advanced approaches such as MPC. The implemented control frameworks share clients for communication, e.g. via MQTT, HTTP or SQL, and can thus be exchanged in a plug-and-play manner. A disadvantage of the current setup is that there is no REST-API available to retrieve the active set-point directly from the user input selection service.

Table 6 Advantages, disadvantages, and lessons learned for the new ICT components (part 3/3).

Component	Advantages	Disadvantages	Lessons Learned
Management of User Inputs, Section 3.2.7	• safe distinction between set-points • integration of user-customizable schedules • fallback plans	• additional cost for managing multiple set-point sources	• pre-processing of inputs simplifies use of advanced control logics • including fallback plans increases operational reliability
Control Applications, Section 3.2.8	• enable user-centered and predictive control • framework for real-world evaluation	• controller prototypes must be closely monitored	• enable users to override control if necessary • communicate research goals and test periods transparently to users

4.3 Performance Evaluation

In addition to the functional evaluation, we assess the performance of the proposed ICT setup based on throughput and other KPIs. First, we analyze the data throughput in terms of messages transmitted via the edge adapters. Then, we calculate system availability and robustness indicators. The communication path via the edge adapters is selected because it is the core enabler for monitoring and control, and experiences the highest data traffic load. All results presented in the following performance analysis are based on a data-set from the time-series database ranging from 01 January to 31 March 2024.

4.3.1 Edge-Layer Message Throughput

To reveal typical message rates, we retrieve all available data points from the database, group the data by building (or rather by building identifier, BID) and day and, finally, visualize the distribution of daily messages in the form of box-plots, see Figure 14a. We find the median number of daily messages to be in the range from $4 \times 10^3\,\mathrm{d}^{-1}$ to $3.7 \times 10^4\,\mathrm{d}^{-1}$ for the majority of buildings. In some buildings (`898276`, `c6e1e8`, `67a6e8`), the message rates are a power of ten higher, i.e., in the range from $1.3 \times 10^5\,\mathrm{d}^{-1}$ to $2.0 \times 10^5\,\mathrm{d}^{-1}$.

To identify the short-time loads, we derive message rates per minute for each building. For this we take the original data-set, calculate the sum of messages per minute, and obtain maximum and median statistics. The results are visualized in Figure 14b-c and summarized in Table 7. The behavior of the daily rates is largely applicable to the minutely message rates, while the load differences among the buildings become even more obvious through the median statistics shown in Figure 14c. In that regard, the buildings `898276`, `c6e1e8`, and `67a6e8` exhibit significantly higher loads ($80\,\mathrm{min}^{-1}$ to $102\,\mathrm{min}^{-1}$) than the other buildings ($2\,\mathrm{min}^{-1}$ to $20\,\mathrm{min}^{-1}$). In building `898276`, the high loads originate from measurements that are highly fluctuating such as active

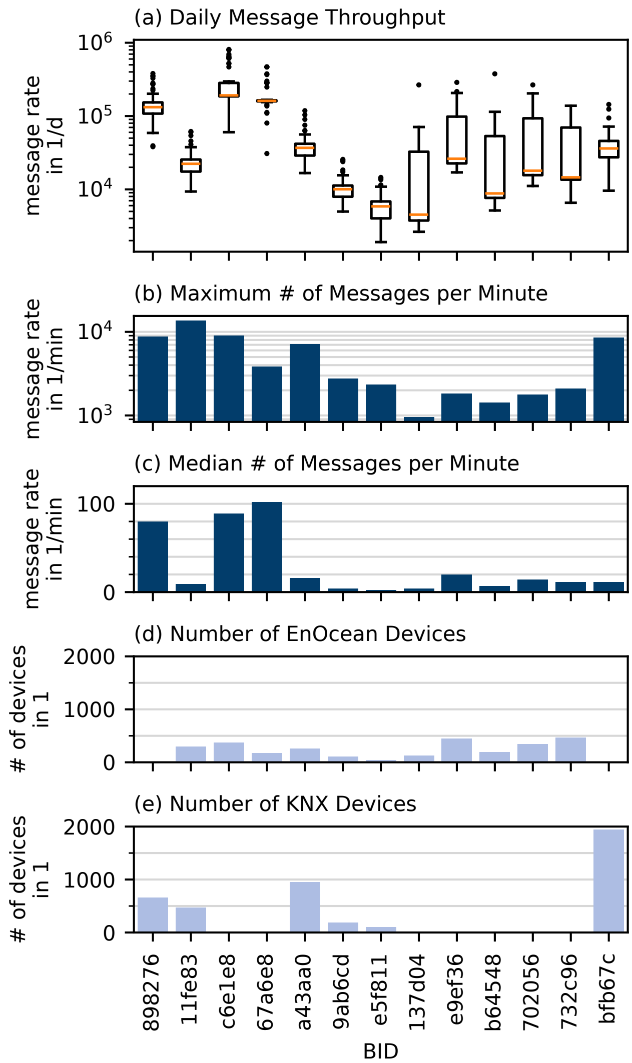


Fig. 14 Edge-layer performance analysis; message throughput in (a)-(c) and number of devices per protocol in (d)-(e), grouped by building ID (BID).

electric power and wind speed, which are only present in this single building. Moreover, it is worth noting that we find the maximum message rate in building `11fe83` with 13 566 min^{-1}, while the median rate there is only 9 min^{-1}. Regarding the buildings `c6e1e8` and `67a6e8`, the comparably high traffic can be explained by cloud-based

Table 7 Edge-layer message throughput and number of devices per protocol grouped by building ID (BID).

	Message rate in 1/min			Number of devices in 1		
BID	Max	Min	Med	Sum	EnOcean	KNX
898276	8793	0	80	661	0	654
11fe83	13566	0	9	768	296	472
c6e1e8	9058	0	89	378	377	0
67a6e8	3858	0	102	174	174	0
a43aa0	7105	0	16	1211	262	949
9ab6cd	2753	0	4	292	105	187
e5f811	2351	0	2	143	41	102
137d04	956	0	4	127	126	0
e9ef36	1832	0	20	450	449	0
b64548	1431	0	7	198	197	0
702056	1768	0	14	344	343	0
732c96	2086	0	11	470	469	0
bfb67c	8568	0	11	1942	0	1942

controllers actively operating the buildings' room heating actuators during the evaluation period (winter to early spring). The respective message rates for traffic from field to cloud and vice versa are listed in Table 8. On average, the message rates for control commands are higher than attribute update message rates.

Table 8 Comparison of message rates for buildings that were at least partly operated by cloud-based controllers.

	Attributes message rate in 1/min		Commands message rate in 1/min	
BID	Max	Mean	Max	Mean
c6e1e8	8421	81	966	96
67a6e8	3840	49	414	73

Figure 14d-e shows the number of individual devices that reported data within the evaluation period, grouped by building and the protocol used for field-level communication. In general, more buildings are equipped with EnOcean devices than with KNX. However, for KNX, the number of devices is up to an order of magnitude higher. This is due to the different treatment of EnOcean and KNX devices. (see Section 3.2.1 to Section 3.2.3). Nevertheless, the number of devices or data points present in a building does not necessarily lead to higher message rates. This can be derived by comparing Figure 14b-e with respect to the two building sets (`c6e1e8`, `67a6e8`) and (`e9ef36`, `b64548`, `702056`, `732c96`). Although the number of EnOcean devices is similar, the median message rates in the buildings of the first set are up to five times higher. This is due to the heterogeneous distribution of device types among the buildings and, probably, also the varying use of the buildings by occupants. Some device types are generally more active (e.g., power meters, CO_2 sensors) or activated more frequently (e.g., window contact and presence sensors) than others (e.g, temperature and humidity sensors). This relationship between message rate and device types present in a building is illustrated in Figure 15. We find that typical building usage patterns are

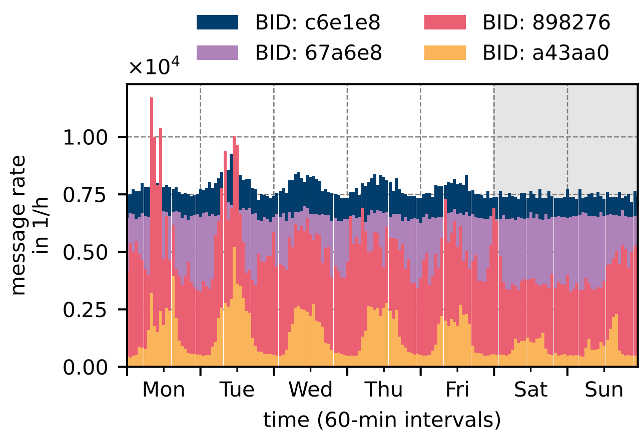


Fig. 15 Hourly throughput for selected buildings over a time-period of one week (12 to 18 February 2024).

reflected in the hourly message rates per day. High message rates overlap very well with the typical 8:00 a.m. to 7:00 p.m. workday window, while message rates before and after this time period drop to a baseline. This effect is pronounced to varying degrees: while in building `a43aa0` the load increases drastically, in the buildings `898276` and `c6e1e8` the difference is less distinct; for building `67a6e8`, only small fluctuations can be determined. Finally, we find that during weekends the message rates, generally, remain constant, although, e.g., for building `a43aa0` slight increases are observable during the day. Depending on the building's orientation and insulation, this behavior can be explained by indoor temperature or luminosity fluctuations depending on diurnal changes in outdoor temperature and irradiation.

4.3.2 System Up-time, Failures, and Repairs

We extend our analysis by calculating common KPIs [127, 128] that quantify the availability and reliability of our ICT setup. First, we calculate the system up-time (availability) for the evaluation period from 01 January to 31 March 2024, see Equation 1.

$$f_{\mathrm{up}} = \frac{\sum_{i=1}^{N_{\mathrm{op}}} \Delta t_i}{\sum_{j=1}^{N_{\mathrm{tot}}} \Delta t_{\mathrm{j}}} \tag{1}$$

Note that N_{op} denotes the number of one-minute intervals Δt in which both edge and data distribution layer were fully available, while N_{tot} represents the total number of one-minute intervals in the evaluation period. To identify intervals of down-time we use a threshold of 5 min. If there is no message received and stored in the time-series database during that time period, we consider the number of intervals between the last message and the resumption of data transmission as system down-time. The resulting availability per building is shown in Figure 16a. A high share of buildings (`c6e1e8`, `67a6e8`, `137d04`, `e9ef36`, `b64548`, `702056`) exhibit an availability of 97 % or higher. In the other buildings, availability is in the range of 93.74 % to 91.31 %, with the lowest availability being recorded for the building `898276`. The comparably long down-time of the building `898276` is due to frequent maintenance, upgrading, and beta-testing in this building, which serves as a test-bed for new edge adapter versions and other infrastructure components. This also reflects in the mean time to repair (MTTR) and

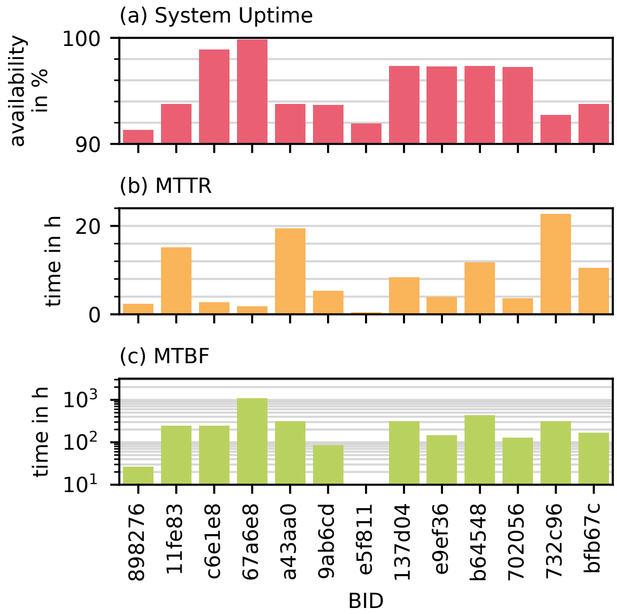


Fig. 16 Key performance indicators on system availability and robustness grouped by building ID (BID).

mean time between failures (MTBF). With the help of MTTR and MTBF [127, 128], we evaluate the resilience of the core components of our ICT setup in terms of the average failure reaction or repair time and the average time-interval between system failures, Equations (2)–(4).

$$t_{\mathrm{MTTR}} = \frac{\sum_{i=1}^{N_{\mathrm{rep}}} \Delta t_{\mathrm{i}}}{n_{\mathrm{rep}}} \tag{2}$$

$$t_{\mathrm{MTBF}} = \frac{\sum_{i=1}^{N_{\mathrm{op}}} \Delta t_i}{n_{\mathrm{fail}}} \overset{n_{\mathrm{fail}}=n_{\mathrm{rep}}}{=} \frac{\sum_{i=1}^{N_{\mathrm{op}}} \Delta t_i}{n_{\mathrm{rep}}} \tag{3}$$

$$N_{\mathrm{tot}} = N_{\mathrm{op}} + N_{\mathrm{rep}} = N_{\mathrm{op}} + N_{\mathrm{fail}} \tag{4}$$

The lower the MTTR and the higher the MTBF, the higher the availability and, thus, the better the performance in cases of failures. For simplicity, we assume the outage time due to failure and the repair time after failure to be equivalent as we do not measure them separately. Hence, the number of repairs (n_{rep}) and the number of failures (n_{fail}) are equivalent, as well as the respective down-time intervals ($N_{\mathrm{rep}} = N_{\mathrm{fail}}$). The reported values of MTTR and MTBF per building are presented in Figure 16b-c and listed together with the corresponding availability in Table 9. Except for the

Table 9 Key performance indicators on system availability and robustness grouped by building ID (BID).

BID	f_{up} in %	t_{MTTR} in h	t_{MTBF} in h
898276	91.31	2.31	26.63
11fe83	93.76	15.14	242.67
c6e1e8	98.90	2.68	242.67
67a6e8	99.84	1.80	1092.00
a43aa0	93.77	19.44	312.00
9ab6cd	93.66	5.33	84.00
e5f811	91.93	0.42	5.22
137d04	97.31	8.39	312.00
e9ef36	97.26	3.99	145.60
b64548	97.31	11.76	436.80
702056	97.23	3.56	128.47
732c96	92.71	22.76	312.00
bfb67c	93.74	10.52	168.00

low MTTR in the test-bed building `898276`, we find comparable MTTR for buildings `c6e1e8` and `67a6e8` (all three below 2.31 h). Slightly higher MTTR are recorded for buildings `702056`, `e9ef36`, and `9ab6cd` (3.56 h to 5.33 h), followed by buildings `137d04`, `b64548`, and `bfb67c` (8.39 h to 11.76 h). The highest MTTR occur in buildings `732c96` (22.76 h), `a43aa0` (19.44 h), and `11fe83` (15.14 h). The lowest MTTR is observed in building `e5f811` with 0.42 h.

In general, we consider downtime, or MTTR, of up to 12 hours to be acceptable in buildings that are not actively operated by an experimental controller. The loss of this amount of monitoring data is acceptable because we primarily use this data for control model training or parameter optimization. Longer repair times, especially over 24 hours, would, for example, reduce the number of full days that can be used to train data-driven models which take into account daily patterns. On the other hand, in order to further reduce repair times, repair capacities and teams would have to be available around the clock to respond quickly to failures. However, this would entail considerable additional costs. Buildings where we actively control the heating or shading system should have a maximum MTTR of 3 h to 5 h to maintain comfortable indoor conditions for the occupants. Although there are kill-switches and fallback control options that will return the building to a safe operating state, prolonged outages would affect user satisfaction and most likely result in a noticeable loss of user acceptance of the experimental controller. Bearing in mind the discussed capacity limits for repairs, we therefore initially focused on achieving the lowest possible MTTR in the area of controlled buildings.

Regarding the MTBF, by far the highest value is recorded for building `67a6e8` with 1092.00 h, resulting, in combination with a low MTTR, in a very high availability during the evaluation period (see Figure 16a). In the other buildings, MTBF in the range of 128.47 h to 436.80 h are found, apart from test-bed building `898276` (26.63 h), building `9ab6cd` (84.00 h), and building `e5f811` (5.22 h). The very short time between failures in `e5f811` suggests structural communication problems. A detailed failure analysis in this building revealed that a configuration error had prevented the building's PLC from automatically restarting. This, combined with exceptionally frequent network problems in this building, led to the low reported MTBF.

The overall availability of the system is in an acceptable range during the evaluation period. For buildings with active controllers (`c6e1e8` and `67a6e8`), it can be considered reasonable based on the main purpose of the setup, which is to enable building energy monitoring and primarily heating control in the context of a research living lab [129]. System availability is the lowest for building `898276`, which is straightforward considering the test-bed character of the building. For most of the buildings, the MTTR is reasonable given the living lab environment. Further investigations are required on three buildings in order to shorten the repair time. Note that we refer to repair times as the time between failure and restoration, not the time or manpower actually spent on repairs. Delays, such as when ICT failures occur outside of regular working hours, distort the picture, as there is no team monitoring the ICT infrastructure around the clock and responding immediately to failures. For critical systems, such as supercomputers or laboratories, there are parallel monitoring systems that trigger immediate repairs in the event of safety-critical failures. At FZJ, this service is provided by the BASD and the TBOD. In other, non-research environments, a similar rapid response team would be required to raise system availability to a level far above 99 % [130].

The MQTT watchdog (see Section 2.2.1) turned out to be a valuable tool to detect failures. It has allowed us to initiate repair workflows swiftly and keep the MTTR relatively short, taking into account the above considerations regarding failure response times. Given the trade-off between MTBF and costs for reliability [131], the performance of our setup can be considered at least solid regarding most buildings and in some cases even better than that [130]. However, further efforts must be made to increase availability. Although reported repair times do not directly reflect actual repair times as mentioned above, repairing connections to PLCs continues to consume significant resources. Network issues were responsible for many of the outages. These should be investigated further and mitigation strategies discussed with the network operator, including moving PLCs to a more stable physical network. In addition, PLCs must be thoroughly checked to identify existing misconfigurations and prevent them in the future.

4.4 Use Case: Real-world Building MPC

To demonstrate the presented ICT infrastructure, we experimentally apply an MPC controller to a real-world building space. The room is part of the test-bed building (BID: 898276) [36, 121, 132] and is equipped with Venetian blinds, high-temperature hydronic radiators, and an underfloor heating. The Venetian blinds are controlled via the vertical position of the slats. The heaters are controlled via valve opening set-points. Wireless EnOcean sensors measure room air parameters such as temperature, humidity, and CO_2 as well as window and door opening states. A KNX multisensor detects presence using high-frequency technology and another KNX sensor estimates the number of people in the room using camera-based person detection. All devices are connected to a KNX field-bus. An edge gateway links the KNX bus with the data distribution infrastructure though an adapter script (see Section 3.2.4). The available data points for the room are retrieved via the KNX REST-API (see Section 3.2.1). The resulting blind and heating control set-points are then assigned to the control outputs of the MPC (see Section 3.2.8). The MPC's objective is to minimize energy consumption for heating and lighting as well as occupant discomfort. The air temperature comfort range is set to 19 °C to 21 °C during typical working hours (i.e., between 08:00 am and 17:00 pm on weekdays) and to 17 °C to 24 °C during unoccupied periods (i.e., between 5:00 pm and 8:00 am).

The MPC was deployed in the building for three days to assess how well it integrates with the ICT infrastructure. An in-depth description of the MPC, including forecasting, modeling, problem formulation, and results from a longer evaluation period are out of the scope of this paper. They can be found in [121]. Instead, we will discuss the performance of the ICT infrastructure during the experiment and the integration effort in the following: The communication between the control framework and the MQTT broker as well as the connection between gateway, adapter and MQTT broker proved to be reliable. There were no unexpected disconnections during the entire experiment. Furthermore, the communication between sensors, actuators and the remote MPC was near real-time with delays in the range of a few hundred milliseconds. This is reflected in the good control results for the room air temperature, see Figure 17. The controller is able to stay within the specified comfort limits, except for a short-term violation of

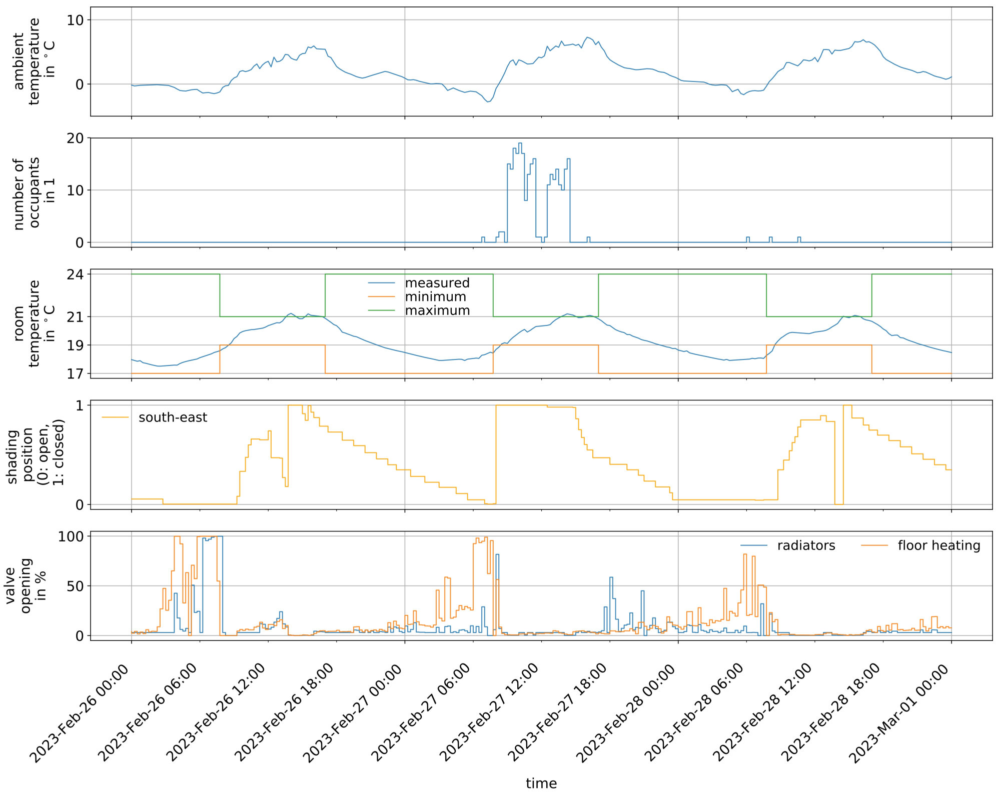


Fig. 17 Results of the application of MPC to an office building space during 26 to 29 February 2023 with times of varying occupancy; related to [121].

the lower limit at the beginning of each working period. For predicting the expected heat input from occupancy, historical number of person measurements from the CrateDB had been combined with room booking data from the PostgreSQL database (see Section 3.2.8). This integration allowed the controller to take advantage of night setbacks while anticipating varying internal gains during certain time periods. The live data visualization (see Section 3.2.5) supported during the initial debugging of the edge-to-field data transmission and the building's metering data could be successfully monitored alongside the room-level data to observe interactions between building-wide HVAC control and radiator operation.

Throughout the experiment, users could not override the temperature set-points, but they could interact with the blinds via a wall-mounted HMI. However, no interaction took place, suggesting a high level of user satisfaction with the blind control strategy, at least during the short experiment. We noticed that the lighting was adjusted to the light conditions, probably due to the shading operation. Based on this, lighting control could be a valuable addition to the MPC controller in the future. For detailed studies on user interaction based on the ICT infrastructure presented, readers are referred to Ubachukwu et al. [114, 116] for heating systems and Derbas et al. [133, 134] for shading systems. For an overview of field device specifications, see Althaus et al. [36] and Zimmer et al. [132].

In addition to good integration with the ICT environment, the experiment also revealed some limitations. For one, mapping the available data points to the controller outputs required considerable effort. Further standardization of the data models and more intuitive access to the device context would help to automate the process and ensure better transferability. Second, we found that radiators and underfloor heating have different response times due to their different actuator technologies (EnOcean and KNX, respectively). This had to be taken into account in the communication between actuators and controllers in order to maintain high control quality. This logic could be outsourced as a service to facilitate the connection of devices to a controller. Ultimately, however, it remains a feature of the devices that must be considered when selecting the technology.

4.5 Advantages and Limitations

The presented evaluation stresses the importance of continuous system monitoring based on KPIs. It enables sustainable improvement and further development of the ICT infrastructure. As outlined in Section 1.1, related studies do not report a comparable evaluation of the ICT infrastructure. Some studies [32, 33, 35, 46] cite hurdles encountered when applying MPC to buildings, but none have conducted a thorough assessment of their approach to interface with real buildings. This may be due to the limited size of the studies in terms of experiment length or building spaces covered. However, we find that including a detailed assessment of infrastructure and implementation hurdles is valuable. It increases visibility of technical and non-technical integration aspects and opens pathways beyond established building automation structures. This is evident, for example, in the considerable interest in more detailed descriptions of integration, such as those provided by, for example, Narayanan et al. [55] and Blum et al. [35] or structured approaches to close the gap between control algorithms developed in research and their practical adoption, e.g., by Eser et al. [135]. This work contributes to the lack of knowledge in these areas by revealing integration options for existing and new ICT, presenting IoT-enabled user engagement and building control components, and an assessment of both the functional and operational performance based on KPIs.

The assessment of functional performance also showed that an IoT-enabled approach can reduce effort in large-scale, multi-stakeholder environments. Such environments differ significantly from setups in which only the BAS or BACS is interfaced [42, 43, 45, 57]. Although, for example, Hilliard et al. [19], West et al. [46], and Winkler et al. [32] involve users through web-based tools, the number of users is relatively small and the duration of the experiments short. As a result, the requirements for application stability and depth of integration with other services are rather low. The service-based integration of data collection, storage, and distribution with user- or management-oriented applications, such as the Energy Dashboard Suite or WALDO presented in this study, demonstrates how future research studies or commercial investigations could further leverage IoT principles in this regard. In this context, the large scale of the approach presented here is a highly valuable feature.

Despite the many possibilities arising from our work, we recognize the following limitations: First, the reliability of the system is not yet at the level required for commercial use, and IoT integration should be developed further, e.g., to facilitate data accessibility. Second, the building requirements and existing ICT components at other facilities may differ significantly from those at our site. While common systems such as energy metering and centralized HVAC control may be available in most managed facilities, technologies and infrastructure layout may be completely different. To account for this, we have focused on the overall benefits of integrating existing systems and ensuring compatibility with other ICT components, and have attempted to derive universal best practices. Third, this study does not directly present ready-to-use technologies or software to overcome some of the identified barriers during practical adoption of advanced building control as, for example, Eser et al. [135]. Nevertheless, we believe that our work, in combination with such tools, can significantly facilitate and accelerate the adoption process.

5 Conclusions

With this study, we dive into the design process of an ICT infrastructure that enables the realization of user-centered building operation concepts. By presenting integration strategies for existing ICT systems and introducing implementation strategies for additionally required components, we aim to encourage the use of more comprehensive ICT setups during the adoption of intelligent building control. Embedded in a large-scale living lab, we show how to leverage IoT principles to establish a flexible ICT infrastructure of well-interconnected services covering aspects of both building operation and management. Through a thorough evaluation of ICT functionality and operational performance in terms of message throughput, availability, and repair times, we not only evaluate the proposed setup, but also highlight the value of including such an evaluation in future real-world studies. In a final investigation, we successfully apply an MPC for the operation of heating and shading in a real-world office space by leveraging the developed ICT setup.

In terms of quantitative results, we find an acceptable ICT system availability for the majority of buildings (>97 %) and a higher availability (≥98.90 %) for buildings that are actively operated by experimental controllers. For the large majority of buildings, average repair times below 12 h are revealed. With respect to the controlled buildings, the average repair time is significantly lower (≤2.68 h). During the three-month evaluation period, most of the downtime was caused by network interruptions and misconfiguration of the edge gateways.

Besides, we report the following conclusions on the development process and the ICT setup's operational performance in a living lab. These conclusions should be considered in similar or future developments:

- To keep integration costs low, start by analyzing existing systems and developing integration paths with relevant stakeholders. When implementing new ICT components, conduct a thorough analysis of use cases to avoid costly iterations.
- Data harmonization and standardized communication interfaces are crucial for efficient data processing. Proper data modeling based on applications and use cases is essential.
- Including heterogeneous data sources is hard. Flexible, expandable solutions for data handling, storage, and conversion are advantageous.
- State-of-the-art software, IoT principles, and DevOps strategies increase interconnectivity, reliability, ICT development and deployment process standardization, and scalability.

The evaluation of our ICT setup has revealed potential for improvement regarding data accessibility, distribution and storage. We plan to improve the ICT setup by using FIWARE [62], an IoT middleware solution that distributes and stores live data and manages device metadata. We also want to standardize device identification, represent relationships between entities, and integrate data validation. We will improve data modeling and enhance software on PLCs and edge adapters to increase system availability and reduce outages. Finally, we aim to evaluate more intelligent controllers in an expanded range of buildings and applications.

Abbreviations

ADS	Automation Device Specification Protocol
API	Application Programming Interface
BACS	Building Automation and Control System
BASD	Building Automation and Operating Services Department
BEMS	Building Energy Management System
BID	Building ID
CD	Continuous Delivery and Deployment
CI	Continuous Integration
COV	Change-of-Value
DH	District Heating
DDC	Direct-Digital-Control
DUT	Data Unit Type
EEP	EnOcean Equipment Profile
FB	Function Block
FZJ	Forschungszentrum Jülich GmbH
GUID	Globally Unique Identifier
HMI	Human Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
IaaS	Infrastructure as as Service

IaC	Infrastructure as Code
ICT	Information and Communication Technologies
IoT	Internet of Things
JSON	JavaScript Object Notation
LAN	Local Area Network
LLEC	Living Lab Energy Campus
MPC	Model Predictive Control
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
PLC	Programmable Logic Controller
RBC	Rule-based Control
REST	Representational State Transfer
SCADA	Supervisory Control and Data Acquisition
SQL	Structured Query Language
SSL	Secure Sockets Layer
TABS	Thermally Activated Building Structures
TBOD	Technical Building Operation Department
TLS	Transport Layer Security
VLAN	Virtual Local Area Network
WALDO	Web Application for Device Organization

Declarations

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests.

Ethics Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

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Authors' Contributions

F.R. and P.A. defined the structure of the manuscript and led the writing and editing process. F.R., P.A., E.U., S.J., P.L., C.K., M.O., L.W., T.S., and A.X. developed the methodology and contributed to software, writing, and visualization. F.R. and P.A. contributed to the functional evaluation. F.R. conducted the performance investigation and curated the data. M.M. contributed to the experimental control study. L.W., T.S., A.X., and D.M. provided resources and supervision. A.X. and D.M. handled project administration and took care of funding acquisition. All authors reviewed the manuscript carefully.

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