IoT platform and infrastructure for data-driven optimization and control of building energy system operation

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Abstract. Optimizing the operation of energy systems as typically found in buildings, plants, and districts has the potential to greatly reduce primary energy consumption and maintenance expenses. Due to the complexity and nontransparency of these systems, costs of implementing optimizations may well consume or exceed potential savings. Data-driven methods for the automatic analysis and optimization of energy systems represent a promising solution to this dilemma. In this paper, we present a real-world IoT cloud platform for automatic data-driven analysis and control of energy systems that promotes usability, scalability, and efficiency. The presented solution has been successfully developed to market maturity in agile collaboration with industry and research, and is now commercially offered by aedifion GmbH.

1. Introduction
A detailed survey among manufacturers, planners, installers and operators of building automation systems in Germany shows that more than 70% of automation systems are operated suboptimal in terms of energy efficiency and supply quality [1]. Unfortunately, the costs of analyzing these systems and implementing optimizations often outweigh the rewards and thus mandate low-cost, easy-to-use and time efficient tools. Data-driven methods, maintained, scaled, and deployed in the cloud, offer great potential in this respect. In this paper, we present an IoT cloud platform designed from the ground up with the goal of automated data-driven analysis and control of energy systems. To this end, our platform offers plug-and-play data acquisition and storage, (semi-) automatic structuring of acquired data, a range of automatic monitoring and analysis methods to identify optimization potential, as well as methods for active automatic control of energy systems in order to realize it. Figure 1 shows a high-level overview of the inner workings of the presented platform. We attach a special edge device to the automation or monitoring network of the target building, plant, or energy system (left), where it automatically discovers all datapoints, readable as well as writeable. The edge device logs all data points periodically and streams to the IoT platform (middle), where data is stored, structured, and made available protected by role-based access control. Further, the platform offers runtime environments for preprocessing, analysis, and control algorithms. A tailored frontend (top) and application programming interfaces (APIs, right) are available for users and third-party software to interact and integrate with the platform.

The focus is on the practical applicability of the presented platform. The platform, thus, has been and will be further developed in close collaboration with its users in industry and research. This allows...
exploitative prototyping of new features with short feedback loops. Once a prototype gains user acceptance, it is further developed in evolutionary steps until it reaches a technology readiness level which enables generic and scalable use across different plants, buildings, energy systems, and even districts. Compared to other IoT platforms, we have designed an all-in-one solution to equip or retrofit such systems for advanced automation applications and efficient operation. Nevertheless, all services of the platform are publicly documented and available as independent modules and microservices ready for integration in a cloud-of-clouds environment [2].

The remainder of this paper is structured as follows: In Section 2, we discuss the novelty of the presented platform followed by a detailed survey on data acquisition and management in Section 3. Section 4 and Section 5 provide an overview over the applicability of the platform for automated analysis and control, respectively. Section 6 discusses system and data-security. We conclude this paper in Section 7 and offer examples of real-world applications of the presented platform.

2. Novelty of presented process and IoT infrastructure
Data-driven optimization of energy systems requires three steps: 1) Data acquisition, 2) data analysis and derivation of optimization measures, and 3) their implementation. Table 1 summarizes the novelty of the presented process by comparison to the state-of-the-art as discussed in the following.

| Process step                   | State-of-the-art                                                                 | Developed process                                                                 |
|-------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Data acquisition              | • Manual configuration • Costs per data point • Energy system knowledge for data point selection required • Local data storage and batch access | • Plug and play • No data point specific costs • Data streaming to platform • (Semi) automated structuring of data into semantic models |
| Data analytics                | • Manually via data visualization • Scarcer: use of algorithms • Manual mapping of data points to algorithms required | • Automated analysis and interpretation • Data visualization and key performance indicators (KPIs) • Automated derivation of optimization measures |
| Implementation of control measures | • Commissioning of the manufacturer of the automation system | • Implementation via platform’s write feature, also utilisable via platform’s API |

State-of-the-art processes are limited in their depth from the outset, since data acquisition is associated with data point-specific expenditures. This leads to a limitation of the historized data points to those that are most promising for analysis and optimization of the energy system, inherently causing expenses for limitation decisions and leaving a huge optimization potential untouched. Technical options for the
realization of data historization range from local storage (e.g. CSV, HDF5, SQL databases) to the implementation of data logger hardware, each requiring manual setup to acquire the preselected data points. Advanced solutions allow remote access to locally stored data via VPN or data transfer via email. In contrast, we solve this challenge via a plug-and-play installable edge device which enables high-frequency data collection of all data points on site and data streaming with milliseconds latencies to the IoT cloud platform where the data is historized. Thereby, expenses for data acquisition are drastically reduced and data accessibility in the aspects of data point availability, time resolution and simplicity of data egress via the platform’s API is improved at the same time. [3,4,5]

Data-driven analyses, interpretation and derivation of optimization measures is mostly realized by manually interpreting trends of time series using visualization or, less frequently, by results of algorithms [3,4,6]. Applying algorithms remains a laborious manual process, due to the assignment of data points. Our presented process provides automated classification of each data point by applying artificial intelligence (AI) and meta data extraction from control systems. This enables semi-automatically mapping of data points to a semantical data model for energy systems and hence to generic algorithms that perform automatic analysis, interpretation and derivation of optimization measures. Regardless of the interpretation method, implementing identified measures economically remains challenging. Often an adjustment of control parameters or the control itself yields to cost-efficient and significant optimizations of energy systems which is solved to the state-of-the-art by commissioning the control system’s manufacturer. The IT infrastructure applied for the presented process enables reliable writing of values directly into the control system, thus allowing for direct, low-cost implementation of regarding measures. As portrayed, the novelty of the presented process is revealed in the redesign of the individual steps of data-driven optimization and control processes, and in the streamlining and automation of the process itself enabled by the tailor-made IoT platform and ICT infrastructure. The new technology allows leveraging optimization potentials that cannot be economically realized with the state-of-the-art.

3. Data Acquisition and Management

Consistent, comprehensive, and current data sets are the basis for all data-driven analysis and optimization approaches. Therefore, ingress, combination, storage, management, and egress of various types of data from different sources and to different destinations are central tasks in the presented platform.

For data acquisition a preconfigured industrial PC is used as an edge device. Usually, energy monitoring and building automation TCP/IP networks are physically or logically separated from the Internet. In such configurations, the edge device is applied as a gateway. When connected to the Internet, the edge device automatically registers with the cloud platform and, from thereon, its status and system health is continuously monitored. Through a fully encrypted tunnel established on-demand, the edge device is maintainable, reconfigurable and serviceable with upgrades. From a building operator’s perspective, commissioning of the edge device is thus entirely plug-and-play.

Data is logged from all technical building equipment, such as building automation, energy monitoring, plant control technology and, if desired, any other relevant IP based systems. For this purpose, the edge device connects to common automation protocols (e.g., BACnet, KNX, Modbus), application servers (e.g., OPC), as well as local legacy databases (e.g., MS SQL). Like the platform, the edge device provides concise APIs that enable and simplify local or remote configuration.

We log current states of all data points of the automation system periodically. The achievable logging frequency is limited by the performance of the queried data source. In practice, frequencies of the order of 0.1 Hz range are attainable even in large automation networks with several thousands of data points. To ensure communication and storage efficiency, only change-of-value (CoV) events are logged. Equidistant data acquisition is available on demand. Furthermore, automation protocol inherent meta data of data points and devices is logged. The collected data is streamed to the cloud platform using the MQTT protocol on top of TLS. Additional mechanisms, such as local data buffers, improve the robustness of the bare MQTT protocol. The platform’s MQTT API is accessible to third parties, enabling data streaming from other data loggers, I/O modules or PLCs.
In addition to the native logging functionalities, the presented platform is equipped with a growing number of connectors to several web-based data sources, such as weather data, occupancy information, and third-party IoT cloud platforms. These connectors allow the platform to act as a virtual data logger by actively querying or subscribing to the APIs of these sources. Such connectors can also be developed and operated outside the platform, utilizing the MQTT or file upload API of the platform for data ingress.

Additionally, the platform provides means to create virtual datapoints. They are generated by pre-defined stream processes running calculations on one or more actual, physical data points. E.g., the determination of a heat flux from a temperature difference and a volume flow. A virtual data point provides its output in the form of a new data point on the platform. Thereby, every data point related service, e.g., alarming or visualization, becomes automatically available on virtual data points as well.

Due to the high number of data points in building and energy systems, meta data on those data points are key to structuring the acquired data such that it can be fed into analysis or control algorithms. In order to systematically store and link meta data, simple key-value tags structures have proven effective [7,8]. Part of the presented platform is an AI that automatically enriches collected data with tags using classification algorithms on a datapoint’s time series and meta data. E.g., temperature and CO2 measurements are recognized with an accuracy of over 99% [9]. In addition to manually adding tags and validating the auto-generated tags, users can link data points to component data models, and implement alternative data point naming schemes. It is this combination of time series data with semantic modelling that forms the basis for automated data-driven analysis, optimization, and control of energy systems. The meta data is stored in a relational database, while high-resolution time series data is stored in special time series databases that are optimized for time-based read and write queries. The platform provides several management services on data points, e.g., filtering or fine-granular access rights. The frontend and APIs allow for precise use of each of these available management features. While the API is designed according to the REST standards, time series streaming is realized using MQTT, a de-facto standard for this task. Built upon the platform’s frontend and APIs, different human-machine interfaces (HMIs) are offered. A freely available Excel add-in which enables one-click integration of time series data into Excel. Chat bots, speech-control, 3D visualization with integrated live data are other examples.

4. Analyzing the collected data

Automated analysis of the collected time series data is possible via semantic descriptions of its data points. The goal is to achieve transparency and to generate recommendations for optimization. Data points are automatically mapped to generic analysis algorithms by comparison of their semantic description with the expected meta data of input placeholders of a given analysis function. E.g., an algorithm to evaluate cycle rates of heat pumps will expect the meta information of a data point being an operational message (derived by AI) of the specific heat pump (currently added by user). The algorithm itself derives several key performance indicators like number of starts per period, average operating time per cycle, minimum shutdown time, etc. Results of the analyses are passed to a decision algorithm which utilizes digitalized engineering knowledge to qualitatively evaluate the results and automatically derive recommendations for optimization of the technical equipment analyzed. In the presented example one measure to reduce high cycle rates is to adapt the shutdown limits of the condenser output temperature to the maximum extent possible, thus enlarging the operating range of the heat pump.

Stream and batch processes are available for analysis. Stream processes are operated continuously in almost real time, thus are suitable for time-critical services, e.g. alerts. Batch processes are executed on historic data and enable complex determinations. Analyses are available as microservices of the platform and utilisable via API and HMI. For easier integration with third-party services, we offer a so-called imperative API that enables on-demand analysis of data sent to the algorithm on API endpoint call.

5. Writing control values

An important part of the data-driven optimization process presented in this paper is the cloud-based writing of values to local control systems. In addition to the possibility of adapting control parameters such as heating curves and control parameters, the possibility to directly write values to automation
systems also enables operation of cloud-based control algorithms. The writing feature allows the direct implementation of optimizations identified by analyses, without the need to commission the manufacturer of the automation system. We designed an interoperable protocol for this communication.

Through the interaction of the cloud platform with the local edge device, it is possible to write setpoint values as well as all system inputs and outputs via the platform's HTTP API, allowing reliably overwriting of the local building automation system without affecting safety-critical functionalities or violating individually defined thresholds. Single setpoints or entire sequences of control commands, so-called schedules, are utilized. Further, implemented safety functions constantly check the connection between edge device and platform. These functions allow for configuration of actions in case of connection termination, e.g. timeout thresholds until a schedule will be revoked and the data point will be reset to a default value allowing for return to the basic automation system control value.

6. IT-security and data privacy

Concerns about IT security and data privacy are major hindrances to the real-world application of internet-based innovations and thus the presented process. To proactively address these concerns and resolve them, we considered and implemented the maximum of both IT security and data privacy features in every granular module of the IoT platform.

In order to exclude the risk of a network or subscriber inquiry overload of an automation network due to the technology introduced for data logging, the response times of the data sources are monitored, and the query frequency of the data collection is adapted accordingly. The writing of values to the automation system must be enabled on a project- and data point-specific basis, limiting the writable value range and, if the BACnet standard is used, the writable priority. The edge device establishes an Internet connection for data exchange with the platform without establishing a direct connection between the building automation system and the Internet by only accessing the building automation locally. External access to the local network is not required at any time. All required connections, even for writing control values back to the automation system, are unidirectional communication to the configured servers, only requiring communication to the cloud platform via ports 22 (reverse SSH tunneling for remote maintenance, kept alive only for access period), 443 (HTTPS for periodic monitoring of the accessibility and functionality of the edge device) and 8884 (TLS encrypted streaming via MQTT protocol). The edge device explicitly communicates to configured server addresses of the IoT platform. Therefore, local networks can remain completely protected against external access, e.g. by existing firewalls. For special applications remote maintenance via VPN and batch upload of data via HTTPS, or air-gapped deployment can also be realized. However, these solutions require a significantly higher setup and maintenance effort and limit possible streaming and close to real-time data services like alarming.

All data transferred over public Internet either between edge device and cloud platform or between platform and user terminals is secured by TLS 1.2 and SSH 1.5 / 2.0 end-to-end encryption. The identity and authenticity of the platform is ensured by a valid 2048-bit RSA server certificate which is verified by a root certificate authority accepted in common browsers. The authenticity of the edge device and its authorization to use the communication channels and data services is checked and guaranteed either by username and password or by client certificate. The used encryption technologies and data transfer protocols HTTPS, MQTT, TLS and SSH are well tested and validated standards for the required tasks.

Further, the platform is protected against DDoS attacks and has a multi-redundant connection. All services are hosted exclusively on dedicated servers, thus eliminating possible risks due to co-location. In addition, all services and data are consistently encapsulated and separated. A dedicated database is operated for each project. Virtual users in the backend, for example microservices, but also real users have by default only those rights (privileges) which they actually need for their intended purpose. For example, a data-evaluating, i.e. reading, service may not write data points by default. All processes are separated from each other at system level by container virtualization and only interconnected in dedicated virtual networks if necessary. Data is accessed via personalized user accounts. Users are authenticated against a dedicated identity provider using the Open-ID Connect protocol. Third party identity providers, such as OpenID, Google, or GitHub, can be integrated and used on demand.
To meet GDPR compliance, a role-based access and right management is utilized which is characterized by a reusable and arbitrarily granular definition of authorization levels for data point sharp read and write privileges. Roles are individually linked to users’ identities and can be controlled, tracked and revoked accordingly. Optionally, certain data points or entire areas of the building can be excluded from data collection, either through technical prevention in advance, for example by network masking or VLANs, or through flexible configuration within the data acquisition software. For de-facto personal data or data that can be related to a person, a completely encrypted data storage can be realized.

7. Conclusion
The presented IoT platform for data-driven optimization and control of buildings and energy systems is currently in operation at nineteen different sights, e.g. at the Energetikum of the FH Burgenland, Austria, logging about 5 400 data points at a frequency of 0.2 Hz and at the E.ON Energy Research Center (ERC) of the RWTH Aachen University, Germany, logging about 12 000 data points once a minute. The automation of data analysis was realized through a generic analysis framework which combines the collected time series data and meta data of the semantical data model. As a real-world application, a cycle and operating time analysis was utilized on the heat pump of the ERC which automatically identified excessive cycle rates, interpreted their effect to cause avoidably higher wear and energy consumption, and in conclusion derived recommendations to lower cycle rates. Optimization through cloud-based control via the presented IoT platform was proved at the ERC, e.g. by introducing demand-driven control of meeting room ventilation. The control algorithm combined room climate data and its current and future booking status. Further, a weather predictive control of thermally activated components was introduced. In autumn 2018 we achieved a 65% reduction in peak load cooling plant operation in the southern building zone compared to the default heat-curve control of the northern zone for the same period.

These real-world applications of the developed IoT platform and of the process for data-driven analysis and control validate a successful implementation. We developed an all-in-one solution for plug-and-play data acquisition, cloud connection of control networks, automated data analysis, and cloud-based control. The technology proved the potential for scaling and cost-efficient optimization of building and energy system operation. Each module of the process is available as a managed service or microservice, thus ready for integration in third party platforms, services, and cloud-of-clouds environment. Future work will focus on the extension of analysis and control algorithms.

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