A Web Based Data Processing Concept for Building Diagnostics and Performance Evaluation

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Abstract. Buildings are responsible for a major amount of the annual energy consumption. A detailed recording and evaluation of building data could provide a deeper understanding of building operation schemes and the corresponding performance. This could help building owners and operators to evaluate and better understand the actual situation. Based on this (real-time) data an optimized operation scheme can be designed and implemented for future time steps. Additionally, a more detailed understanding of the impact of previous building systems interactions will be possible. The building automation industry and the related service provider sector are actually providing proprietary solutions for data logging, visualization and energy optimization. Such solutions are regularly integrated into their own specific software of the used proprietary building management solutions. As an alternative, we suggest an Internet of Things (IoT) and web services inspired concept for the implementation of a generic web service for building diagnostics. Our suggestion encompasses a holistic performance evaluation that considers both the energy consumptions and delivered building service. In this contribution, a general design of a web service based solution is presented and the future possibilities for data access from various sources are discussed. Furthermore, details of actually developed and demonstratively implemented software components for data preprocessing are presented. Data processing examples for different types of data are included and highlight the potential of such web-based approaches. Moreover, possibilities for improved building control by the use of web services for operation schedule generation or model predictive control are illustrated and critically debated.

Introduction

The climate change, as documented in the latest IPPC assessment report, [1] and the predicted depletion of fossil energy sources [2] will strongly influence our future life. Moreover, they will lead to a change of our society, the energy sector, and the different industry domains. These changes will also influence the building sector and future developments towards sustainable and ecological building design and operation.

Current climate-change mitigation efforts target a significant reduction of the global emission of greenhouse gases, as well as a shift towards renewable energy resources. Recent international agreements, such as the latest United Nations Agreement in Paris [3], demand considerable reductions of greenhouse gases emissions. Given the high potential regarding emission reduction and implementation of renewable energy sources in the building sector, the built environment can be said to play a key role in reaching these ambitious goals. Actually, the EU (European Union) quantifies the related amount from the building sector with 40% of the total European energy consumption and with 36% of the CO₂ emissions [4].

To reduce the building related energy use both in an efficient fashion and in a reasonable time frame, it will not be sufficient to just address new buildings. Actually, only a small fraction of the European building stock could be specified as at the end of its lifetime. Therefore, investigations on
the building sector have to focus on energy related improvements of the existing building stock in a much higher amount, and a more adequate way. Accordingly, the “Energy Performance of Buildings Directive” [4] from the European Commission specified the necessary procedures to evaluate the energy performance of buildings, not only based on the energy demand predictions considering the design assumptions, but also using certification practices, which consider the real energy demands. The operation of buildings and the optimized control of various integrated systems is a significant factor to achieve the desired performance goals (energy use, acceptable and pleasant performance in terms of thermal comfort and air quality).

An appropriate design together with an adequate implementation of the building control systems depends on detailed understanding of the related building systems and components. Moreover, a clear understanding of influencing parameters, such as external weather conditions and the occupant usage patterns, are needed to define optimal operation regimes. Consequently, strategic data monitoring, together with detailed diagnostics, seems to be a necessary precondition for planning and evaluation of potential improvements of existing systems, or – alternatively - for the development of new, improved system and control concepts.

The actual developments in the IoT area and the availability of technology used in the web-domain seems to provide some alternatives to existing cost expansive, mostly inflexible solutions, as used often in today’s building automation domain. The resulting new possibilities of these technologies have the potential to change the existing manners regarding data collection, performance evaluation and control in buildings.

**Web Services for Building Diagnostics and Performance Evaluation**

Building performance evaluation gains importance due to the setting described in the previous section. A detailed understanding of energy consumption data and the interpretation of internal and external states provide necessary information needed to optimize building operation patterns. The actually, commonly used building performance evaluation solutions are regularly deeply integrated in manufacture dependent building management software solutions and mainly target building management and energy issues. A reason for this specific focus could be that the market players are still focusing on the needs of their own customers from the building operation and facility management domain. These business domains face increased pressure to reduce the operation related energy consumption of buildings. Nearly all of the commonly available commercial solutions are dependent to certain specific hardware and software packages. Regularly these packages are compatible only to the products of the specific manufacturer and do not offer interfaces for generic use of the collected data. A manufacture independent generic solution is regarded as unconventional way for the commercial building automation and operation community. The main reason for this could be that building service providers are legally responsible to deliver a certain performance. This also includes a nearly constant operation with a minimum of fail outs and errors in operation. In this context the usage of well tested and proved commercial building automation systems (BAS) and building management systems (BMS) is considered to be a more secure way than the use of unconventional hard and software for daily operation.

Recent developments in the consumer electronics sector and the resulting occurrence of Internet of Things (IoT) in different fields of our daily life, however, will influence the building automation market. All future developments, for instance those for data monitoring possibilities and the implementation of more holistic control approaches, will be affected. Web-based access to building management and automation systems already exists for a bunch of different products and communication standards but all of them are unique, mostly manufacture-related solutions and are more project specific implementations. Future developments towards simple and standardized access to BMS-data, similar to the well-known REST-Services used in the web engineering domain, will enable new stakeholders in the domain to access data and to realize more sophisticated
diagnostic and control approaches. Thereby, such services can be physically located outside of the classic building automation system, for instance somewhere in a cloud solution.

Various scientific and commercial developments of web-based solutions for data monitoring and data visualization demonstrate the potential and the need of such approaches. Different end-consumer orientated services are available and could be used to collect required data in addition to the classical BMS-related approaches from the building automation industry. These solutions are more flexible in terms of hardware, integration and realization in existing buildings. The integration of additional sensors and meters into existing building automation infrastructure can be considered as complex, cumbersome, and error-prone, and often result in an extensive and costly adaption of the existing hardware and software. Moreover, it can also raise organizational issues such as conflicting responsibilities regarding the necessary interventions. Most of the commercially available monitoring concepts are manufacturer-dependent solutions with specific hardware and software. In such a manufacturer-specific solution, integration of the recent available smart IoT related products and services for energy metering and internal and external conditions sensing equipment is very challenging. Recent developments for open building management software, such as the BEMOSS [5] (Building Energy Management Open Source Software) platform supported by the US Department of Energy, work on open-source solutions to solve the interoperability problems of existing approaches. The developments in the area of IoT and the existing monitoring platforms of various building related domains, including Xively [6], weather underground [7] and OpenEnergyMonitoring [8] and other building related platforms, enable community and researchers to implement new web-based building monitoring and diagnostic solutions. For instance, the open source MOST [9] project provides an environment for data from different sources, and enables the user to analyze the data and export it after pre-processing. In parallel, other developments focus on the combined control of systems with programming possibilities for end-users. These features are now available in different software applications such as openHAB [10] and Fhem [11].

In contrast to the commercial conventional centralized manufacture depended building monitoring and management solutions, a web-based approach that uses different distributed components for data reading and storage, as well as for the analyzing software parts can be realized with the available web-technologies of the IoT domain. Thereby, it is possible to create an easy-to-adapt, low-cost, and easy-to-setup monitoring infrastructure and data processing platform. This cloud-based solution consists of a number of data collectors or loggers, monitoring services, a building related web service and the users (clients) connected to the Internet. A general architecture schema of the developed cloud-based solution is illustrated in Figure 1. The communication between the different hardware components, as well the software components, is based on a RESTful communication concept. Most of the current data related web service are already offering RESTful application programming interfaces (APIs) and make the integration very easy. The Web Service for building diagnostics and performance evaluation itself is a classic web application implemented in a common web server environment. Data from different repositories (eq. Xively, weather underground and OpenEnergyMonitoring) will be requested on demand, processed and visualized depending on the specific case. Thereby, a combination of data from different domains such as the building management system, schedule data from web calendars, energy records, and weather data, could be deployed to understand and analyze correlations and certain characteristics. Furthermore, a partly-automated control advice generation, as well as the processing of set point schedules, could be realized based on this concept as presented at the end of this contribution.
For holistic building performance evaluations, different types of data-processing methods are required to realize a standardized data representation for following processes. A set of reliable methods for the processing of the raw data in relation to the characteristics of the different data sources and repositories are needed as well. The experiences made in different international research projects focusing on optimized building operation, documented the need of an easy-to-adapt, low-cost, user-friendly, and versatile environment for data evaluation and visualization. Especially data that is needed for system modeling and performance evaluation is regularly not directly available in existing approaches, as provided by the current market players in the building facility and operation domain. Such environments are regularly not flexible enough for the implementation of very specific methods. Open source software solutions are available but also do not fully cover the needs of the related optimization and evaluation tasks. Especially in the case of the open software environments MOST and openHAB, an adaption or extension of existing components implemented in JAVA was not very practical. This led to the development of a flexible software concept that is based on a classical web server approach. Moreover, the utilization of a script language (PHP) for implementation of the distributed software packages was conducted to be compliant with the already presented schema of a distributed web based concept for building monitoring and performance evaluation.

**Data Processing Approaches**

In general, a processing of acquired raw data has to consider characteristics such as datatypes, how it was sensed, processed and how it is stored in a specific data repository. Figure 2 illustrates generically the typical chain from physical value to the final-stored data-element. Depending on the used monitoring technologies and the corresponding implementation solutions, the resulting data points show specific characteristics. This has to be considered in all following data processing procedures. Additionally, the temporal pattern of the data results in different data pre-processing methods, which – if implemented carefully - guarantee that a combined data analysis of data of different special and temporal resolution can be conducted in an easy way.
Recorded building data can be split into two main groups in general, periodic data and event-triggered (or event-related) data. In most cases, the following data processing routines need a set of periodic data with fixed intervals and synchronized timestamps. Therefore, methods to generate discrete values in a manner to represent the averaged raw data value of the preceding interval period were developed. This allows an easy correlation analyses between different parameters. Moreover, it provides the user with the option to export data for direct integration into external software, eq. building simulation tools.

Processing Event-Based and Regularly Recorded Data

Processing of event-based data is one of the major features that is missing in the existing solutions for building management and operation. Such a feature is necessary to preprocess event-related information for further data analyzing processes in a standardized way. In detail, the raw data from such event-related data streams has typically a temporal pattern with irregular time intervals between the measurements and has to be converted to data series with periodical timestamps. Figure 2 illustrates one of the developed approaches for data from an occupancy sensor plotted in blue. The blue dots represent each single measurement and the red diamonds the resulting ones from the generated periodic data set (red line). These are calculated as average of the measurements of the preceding interval period or a repetition of the last measurement if there are no measurements recorded.

![Figure 3. Example of generated periodic data set (red) based on typical data from an occupancy sensor (blue).](image)

Different variations of the previously described method for event-based data processing were developed corresponding to the characteristics of typical event related data streams. Additionally, a component for a threshold function was implemented and enables the user to convert values to a 0 and 1 value only. This can be useful if the data is subjected to analyzing processes using binary input data.

For periodically recorded data, methods for averaging and synchronization of timestamps are needed. In contrast to event-based data, these methods have to calculate timely-weighted averages for timestamp-related intervals or interpolated values in case where values at a specific point in time are needed. Figure 4 illustrates the function of the method for a raw data set from a regularly polled temperature sensor (blue) and calculated timely weighted averages (red). These averaged and timely synchronized data sets are usually needed for thermal and air quality performance evaluations as well for later integration into simulation environments.
Optimized Building Operation

Real building performance very often differs from the predicted one, which was regularly predicted based on the information available in the design phase. This can be partially explained by different usage patterns, improper assumed occupancy profiles, different interactions of occupants, as well as unfitting operation of the building systems as a result of default setups for control systems. Regular systematic evaluation based on collected building data could help to identify possibilities for operation improvements (and also fault detection). Especially new buildings that regularly come with a complex setup of different building systems are in need of an adequate setup of control approaches to reach the expected optimized operation. In this context, it should be considered that especially innovative solutions for heating and cooling, such as passive nighttime ventilation or activation of the thermal mass, are not trivial to control. Because of the very slow response times of such components and systems, a setup with a classic control approach is not very promising. Consequently, the development of predictive control approaches for buildings and systems are the key aspects of several research projects. In the framework of two EU-projects, Campus 21 [12] and RESSEEPE [13], further developments of improved control strategies were developed and implemented, together with the quantitative evaluations of the resulting improvements regarding the thermal comfort and energy savings.

Optimization of Existing Control Approaches

The increasing availability of monitored building data, together with the accessibility of additional data via IoT technologies and related web-service, creates new possibilities for the evaluation of existing control approaches and operation schedules. Regular performance checks will assist to identify inadequate control settings or schedules. As an example, the operation of the hot water circulation could be improved towards a more demand-related schedule, which is derived from occupancy data. Similar potential optimizations of schedules are also possible in other building-related areas. The Campus 21 project was focusing on such software centric building improvement possibilities, where existing building data was used to identify necessary adaptions of the existing building system operation patterns.

Predictive and Model Predictive Control Approaches

New sustainable building designs often use highly insulated building components and high thermal mass in their concept. This leads in general to slow response times of the indoor climate. A classic feedback control such as P, PI, or PID controller is not optimal for this behavior and will end in unnecessary overshoots of the controlled parameter and thus a higher energy demand. New predictive and model predictive control approaches can avoid this by consideration of future trends regarding boundary conditions such as weather and occupant-related influences.
The model predictive control (MPC) is a very common control method in a wide range of industrial process control applications since the 1980s [14]. Currently, only a minority of implementations at the building sector utilizes this type of optimized control. Recent research projects such as Campus 21 [12] and OptiControl [15] focus on real implementation of predictive control methods in buildings. These projects illustrate the application of predictive control methods towards improvements in the thermal comfort and energy performance. The acceptance of such approaches amongst the engineering community is still low. Commonly used programming tools for building control systems still focus on the classical rule based or PID control. As a result, most of the practical MPC implementations are realized as separate components, communicating with a classic BMS setup via gateways and activate the related building systems from external software. This fact, together with the risk of unclear responsibilities, renders the predictive control approach less attractive in real building applications. Existing IT-technologies can be used to setup the components communication in a safe way with hierarchical checks of permissions. The Campus 21 project developed a middleware solution [16] that allowed the external optimization processes to request information and to send control commands to a BMS. The setup used a secure communication in a virtual private network and a unique project related protocol. Moreover, a logical verification of the commands on BMS was programmed to check related values prior to an update of internal set points or control variables.

A concept of a model based predictive control approach was developed and prototypically implemented in three research projects, namely Campus 21 [12], MPPF [17] and NC [18]. All of the implementations used a similar system setup, in which the predictive control approach was implemented as an optimization service executed outside of the classic building automation system. Figure 5 illustrates the setup of the predictive control system and the related data communication via the cloud. The predictive control routine uses historic and actual data from the building together with forecast data from an external source to predict the performance of different actuation possibilities in future time steps. The algorithm includes a genetic optimization process on defined performance indicators and results in related control commands for the next time interval. This optimization process can be executed on a regular interval, e.g. hourly.

![Figure 5. Components and setup of a predictive control service implantation and the related data communication via the cloud between external web services and the building.](image)

**Conclusion**

The work presented in this paper was embodied in different international research projects with focus on optimized operation of existing buildings. Related tasks documented the importance of consistent monitored data for building diagnostics and the need for flexible adaptive building...
monitoring solutions. Based on the knowledge collected in various implementation tasks of these projects led into a development of a web-based concept for data monitoring and processing that enables the implementation of new solutions in the area of building diagnostics and performance evaluation. The presented web-based concept illustrates how low-cost hardware components from the IoT domain can be used for efficient, distributed, and real-time building monitoring. This flexibility of the proposed architecture and components makes the concept highly attractive for short, mid, and long-term monitoring campaigns in research and application. Necessary data for optimization of building systems and operation patterns can be collect and evaluated in combined way by the use of different web services. Moreover, a cloud based concept using web services for the integration of predictive control approaches was presented. With such control approaches, it is possible to capture the interrelated impact of various control actions on indoor environment and to optimize operation of the devices in a holistic manner.

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