A Workflow Model for Setup and Maintenance of an Integrated Building Model for Energy Management

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Abstract

Building automation systems (BAS) are responsible for control, monitoring and supervision of building services, such as heating, ventilation, air conditioning (HVAC), and lighting. The objectives of building automation are energy-efficient operation of building systems in a secure and safe manner while providing thermal and visual comfort, and enhanced life cycle of utilities. As building blocks of BAS, sensors installed in a building typically create large amounts of data during the operation phase. These data provide a basis for improved building energy management. Statistical processing and, more recently, machine learning have been used to interpret sensor data. However, improved reporting and visualization of energy and comfort related parameters in the building operation phase, which are optimized for human interpretation, are relevant to support complementary data analysis by humans. Towards this end, models that combine building information model (BIM) with runtime data from a building energy management system (BEMS) could provide a useful basis. In this paper, we describe workflows for the setup and maintenance of such an integrated building model. Both workflows are developed based on process engineering principles. Tasks in the model setup workflow are tested in an existing medium-size office building. Data modeling and processing issues encountered during testing are described.

Keywords: BIM, BEMS, workflow modeling

1. Introduction

Energy consumption of buildings comprises 40% of total energy use in the European Union. The contribution of building services, especially heating, ventilation, and air conditioning (HVAC) systems, accounts for 50% of energy use in buildings and 20% of total global energy use (Perez-Lombard, Ortiz & Pout, 2008). Building Energy Management Systems (BEMS) are software systems to supervise and control HVAC and systems of the electrical installation domain. They provide thermal and visual comfort to occupants. These services should be provided in an energy effective way. BEMS must respond to dynamic outdoor conditions, take into account a building's spatial structure, building materials, as well as occupant behavior. A fundamental challenge in BEMS is the accurate interpretation of large quantities of data generated by sensors and actuators about conditions in a building to detect defects that may cause inadequate indoor environment quality and/or energy ineffectiveness. Although statistics and machine learning methods have been applied to interpret the generated data (Ahmad, Chen, Guo & Wang, 2018), in situations where such methods are unable to detect defects with sufficient accuracy, human data analysis is still necessary. Of particular interest are information visualization and visual analytics methods to support data analysis (Munzner, 2014). A building model that integrates BEMS data could provide a useful basis for effective human analysis of BEMS data. For example, visualizations of sensor data in their spatial context could be derived from such an integrated building model to help facility managers identify spaces with inadequate thermal conditions (Petrushevski et al., 2018). In this paper, we propose workflows for the setup and maintenance of such an integrated building model.

2. Related work

A BEMS is a system that monitors and controls energy-related systems from mechanical and electrical equipment in buildings (Sayed & Gabbar, 2018). It is responsible for managing energy supply, storage, distribution, and consumption. BEMS focus on preferably low building energy consumption or reduced energy costs as well as a small or minimized deviation from the intended user comfort in the building. Related automation functionality includes power-saving operation, like optimum start and stop control of air-conditioning equipment during non-office hours, adjusted for system inertia. Monitoring and controlling of energy-related systems produce large amounts of data which makes it difficult to extract relevant information for building operation optimization. Hence, methods such as neural networks, fuzzy logic, or evolutionary algorithms can be applied to improve energy management in buildings (Manic, Wijayasekara, Amarasinghe &Rodriguez-Andina, 2016). Molina-Solana, Ros, Ruiz, Gomez-Romero and Martin-Bautis (2017) discuss various use cases for the application of machine learning algorithms on BEMS data. Among others, these include prediction of building energy load, fault detection and prevention, and economic analysis of electric consumption. Trends like Internet of Energy (Vu, Le & Jang, 2018) and fog computing (Shen et al., 2018) are expected to play an important role in future BEMS. Several studies address the integration of BIM and BEMS to optimize building energy use. To improve the operational inefficiencies in the buildings, Tang, Shelden, Eastman and Pishdad-Bozorgi (2019) investigate the integration of BIM and real-time data. Dong, O'Neill and Li (2014) describe a BIM-based database for fault detection and diagnostics (FDD) which facilitates information exchange between static and dynamic real-time operational data sources. The integration of static and dynamic information requires significant manual modeling effort. McGlinn, Yuce, Wicaksono, Howell and Rezgui (2017) propose an intelligent monitoring interface for energy management which formed part of a BEMS. They use BIM and semantic web technologies to integrate static and runtime sensor data to generate rules for building management. Zhong, Gan, Luo and Xing (2018) proposed an ontology-based framework for monitoring indoor air quality, thermal and humidity conditions of a building via integration of BIM and retrieved sensor information with semantic web technologies. Prouzeau et al. (2018) have developed a prototype of a building management system (BMS) that uses visual analytics to provide insight into energy efficiency and comfort in buildings. Gerrish et al. (2017) identify the challenges and potential of applying BIM to building energy performance visualization and management. Data management between design, construction and operation is seen as a key challenge. Autodesk Dasher is a building performance visualization system that displays historical and real-time sensor data in a building model (Hailemariam et al., 2010). Although significant work has been done in visualization and reporting of energy and comfort related parameters, the tasks to setup and maintain integrated building models to support such analysis have not yet been described in detail.

3. Methodology

Workflow models for the setup and maintenance of an integrated building model are proposed. A workflow model formally represents the flow of required activities in a process and their logical sequence (Sommerville, 2011). The workflow models are structured according to five phases in software engineering. In the first *requirement engineering* step, stakeholders and engineers define the system and the constraints for its operation. In *system design,* the overall system architecture is specified. In *system implementation*, modules are implemented and integrated to make the system operational. In *system validation*, the system is checked against stakeholder requirements. In *system evolution*, the system is modified to reflect changing customer requirements or updates. The software engineering phases corresponding to key tasks in the proposed workflow models are shown in

Figure 1.

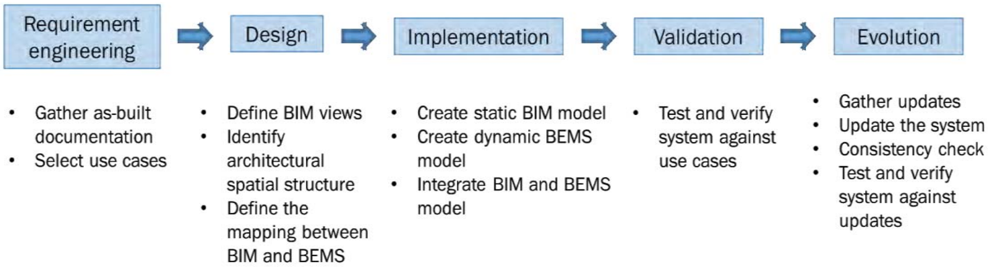

Figure 1: Software engineering phases (Sommerville, 2011) and key tasks in the setup and maintenance of the integrated building model.

The workflow models are represented in the business process modeling notation (BPMN) (Object Management Group [OMG], 2011). Roles and activities in the models are defined based on qualitative interviews with stakeholders and use cases developed in previous work (Petrushevski et al., 2018). A subset of the tasks in the model setup workflow are tested for an existing, medium-size office building. Testing of all tasks is currently infeasible because the integrated building model is still under development. Data modeling and processing challenges arising during testing are described.

4. Model setup workflow

4.1 Actors

Five actors are identified for the model setup workflow (Figure 2). The facility manager (FM) is the end user of the visualization and reporting system and is involved in the setup and maintenance of the integrated building model. He provides as-is information about the building and its BEMS and validates requirements. The BIM modeler is responsible for defining, designing and modeling the building model. He is familiar with the IFC data model. The BEMS modeler is responsible for storing, retrieving and modelling the operational building data. He is experienced with BEMS systems design and operation. The system integrator is responsible for the interoperability between static and dynamic building data and the deployment of the integrated building model.

4.2 Modeling requirements

The initial task in the modeling requirements phase is to gather as-is documentation about the building and its BEMS. Collaboration of multiple actors is necessary to achieve a detailed understanding of a building's condition. This includes determining space layout and usage as well as BEMS components at plant and zone levels. Based on available documentation, use cases for visualizing and reporting energy of comfort related parameters are selected by the actors. Six use cases have been defined in previous work (Petrushevski, et al., 2018). They include visualization of data point (e.g. temperature sensor or set point) values, alarms, preprocessed data, logging data, and energy consumption reporting. The FM validates modeling requirements.

4.3 Definition of model structure

The BIM modeler defines the structure for the integrated building model. A model structure consists of one or more views. A view corresponds to the objects (e.g. rooms, windows, temperature sensors, and HVAC terminals) that are modeled and how they are spatially related. The latter includes defining the spatial structure. A building is decomposed into spatial structure elements, such as sections, zones, floors, and rooms. It is common practice for BEMS data point names to include references to spatial structure elements (Balaji et al., 2016). Dependent on selected use cases, an integrated model may need to support multiple views and hence multiple spatial structures. For example, thermal zones are useful to visualize indoor air data points. A thermal zone is a group of rooms with similar thermal loads that are controlled together. In a corresponding spatial structure, a building may be divided into sections, floors, thermal zones, and rooms. Spatial structures are initially identified separately by BIM and BEMS modelers. The BEMS modeler selects data points that are to be included in the integrated building model. If applicable, additional sensors, such as data loggers or meters, are installed on site. Differences between spatial structures for BIM and BEMS need to be reconciled. These occur when different conceptual models, naming schemes, or identifiers are used. Hence mappings must be defined for objects that are included in BIM and BEMS models.

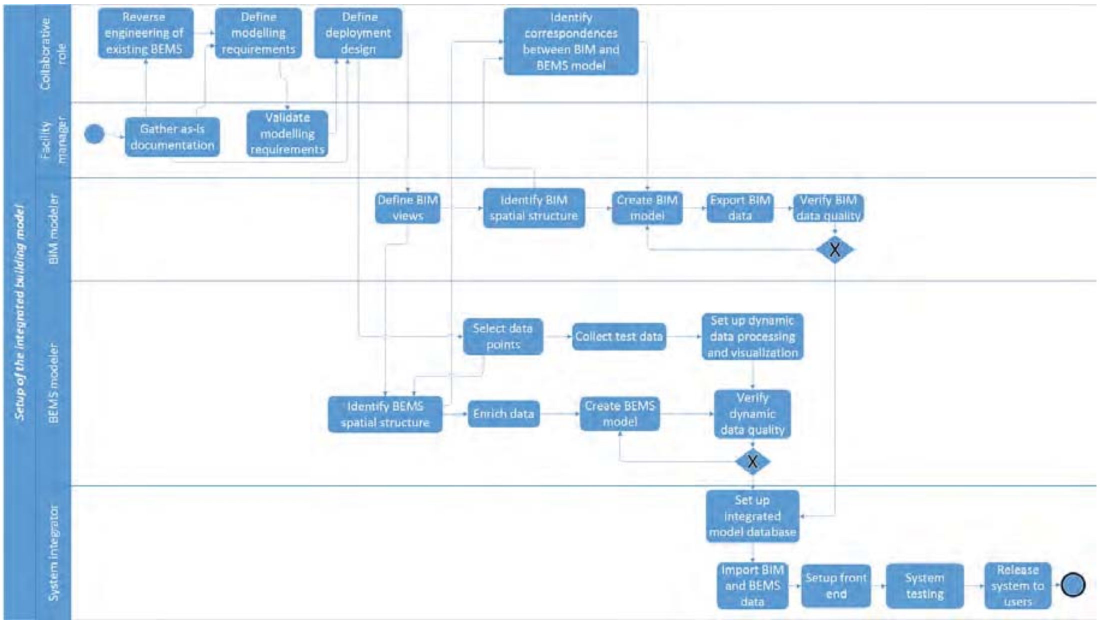

Figure 2: Workflow for the setup of the integrated building model.

4.4 Creation of BIM and BEMS models

Based on the model structure, the BIM modeler creates a building model using a BIM authoring system. The building model includes semantic and geometric object data as well as spatial relationships between objects. The building model is exported from the BIM authoring system using the IFC format (buildingSmart, 2019). This format is chosen because it is vendor neutral, information rich, and supported by many BIM authoring systems. Among available IFC model view definitions (MVDs), the IFC Coordination View Version 2.0 is a widely supported MVD. BEMS specific data, e.g. about devices, may need be exported via custom property sets since coverage of such data in the current IFC release 2x4 is limited. To facilitate updates of the integrated model database, the IfcGUID property must be populated. IfcGUID is a globally unique identifier for IFC objects. In addition to creating the BIM model, the BIM modeler is responsible for verifying its data quality. This can be done with IFC viewing tools or checking systems (e.g., Solibri, 2019).

In parallel to the creation of the BIM model, available information from the BEMS is processed by the BEMS modeler. A list of all data points is prepared. This list can be created automatically for most systems. Often it is necessary to manually enrich the data with additional semantics. Typically, the type of the data point, e.g. temperature sensor reading, and its unit of measurement need to be determined. Next, each point in the list is mapped to a device in the BIM model. Actual time series data are recorded and stored in a database. Time series data must be checked for consistency regarding range and continuity. The installation of additional external sensors may be necessary, for example, to measure temperature, humidity, or air quality at locations where there are no existing sensors. Semantics must be defined for these sensors as well. Finally, the enriched data point list is converted into a machine readable format, such as Comma Separated Values (CSV), JavaScript Object Notation (JSON), or Extensible Markup Language (XML).

4.5 Setup of integrated model database

The fundamental component of the integrated model database is a knowledge base based on well-known ontologies, such as ifcOWL (Beetz, Van Leeuwen, & De Vries (2009)), Brick (Balaji et al., 2016), and BOT (Rasmussen et al., 2017). The knowledge base is complemented by a time series database for sensor readings as well as current and historic set points. The initial step of setting up the integrated model database is to convert the IFC model created by the BIM modeler into ifcOWL. The output of this conversion is imported into the knowledge base. Additional information, such as adjacencies and positions of devices, which are not explicitly available in ifcOWL, are calculated by appropriate tools and integrated into the knowledge base by using concepts and relations of Brick and BOT. Data points as well as the corresponding time series data are integrated by importing the previously created machine readable list of data points. Data from the list are converted into triples which can be stored in the knowledge base. The result is a common database that comprises BIM data, additional explicit location information, data point descriptions, and references to time series data. Information from this integrated model database can be retrieved via a high-level Application Programming Interface (API) or a query language, such as SPARQL. Finally, the system is tested against functional and non-functional requirements and released to users.

5. Model maintenance workflow

The maintenance workflow model involves updating the integrated building model during operation (Figure 3). Examples for updates are the refurbishment of spaces, or the replacement of sensors. Typically, updates are local and do not significantly affect the model structure. Compared with the model setup workflow, the model maintenance workflow consists of fewer but similar tasks. Nonetheless, updates may involve multiple actors. BIM and BEMS modelers need to verify data quality of their changes before the integrated model is updated.

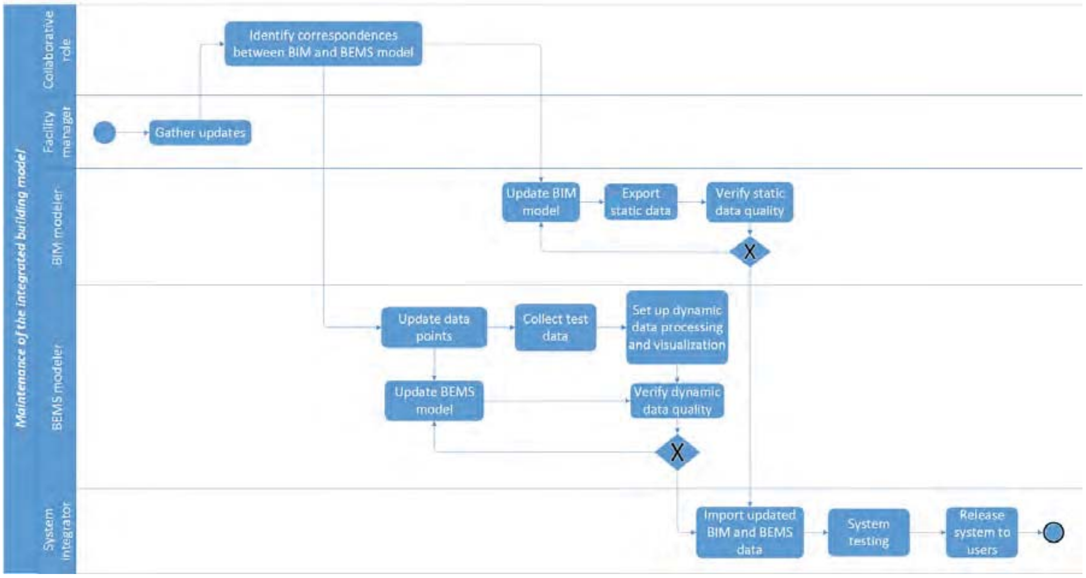

Figure 3: Workflow for the maintenance of the integrated building model.

6. Workflow testing

Tasks in the model setup workflow are executed to create an integrated building model for a test building. The latter is a five-story, medium size office building located in suburban Vienna, Austria. The building is typical for office buildings built in the 1970s and 1980s in Western Europe. The L-shaped building consists of two sections facing East, South, and North.

6.1 Modelling requirements

The as-is documentation of the building consists of 2D vector drawings and spreadsheets for space use, fire safety, air inlets/outlets, and fan coils. A comprehensive written documentation about the as-is BEMS does not exist. Instead, there are HVAC schemes of the building and a list of datapoint descriptions. The rest of the information was obtained through reverse engineering and meetings with responsible building technicians and specialists. The building has three thermal zones: one for each section and one for a meeting room. Each zone is served by a plant that provides a constant volume of heated/cooled air to ensure minimum air change. Spaces are further heated or cooled with fan coils. Unfortunately, no data about their state is available in the BEMS.

Based on the as-is documentation, the use case ‘Visualization of logging data in a spatial context’ was selected to derive modeling requirements (Petrushevski, et al., 2018). In this use case, external sensors are installed to collect data about indoor thermal and air quality conditions, e.g. in locations where there no existing sensors. Required information includes logger locations and readings. The spatial context is modeled by architectural element (space, door, window) and HVAC terminal (e.g. air inlet/outlet) geometries. Space function data are required because they are useful to analyze logger readings. In addition to the containment relationship between loggers and spaces, the space adjacency relationship is required to visualize differences in logger readings between adjacent spaces.

6.2 Definition of model structure

As only one use case was selected, the model structure has a single view which consists of data loggers and their spatial context, as represented by architectural elements (spaces, windows, and doors) and HVAC terminals. In the spatial structure, the building has two sections, and each section has five floors. Thermal zones were not modeled explicitly. Identifying correspondences between the building model and data loggers was a major modeling challenge. This is because object properties in the integrated model database originate in multiple systems which assign different object identifiers. This raises the issue of preserving object consistency when object properties are modified in any system. For example, locations of data loggers are modeled in a BIM authoring system, and logger readings in a time series database. Data loggers are identified in the BIM authoring system by native identifiers and IfcGUIDs. In the time series database, on the other hand, data loggers are identified by their manufacturing identifier. These identifiers were mapped manually map to ensure consistency.

6.3 Creation of BIM and BEMS models

As the documentation of the test building consisted of unstructured data, it was necessary to create the BIM model from scratch. This was done using the Revit Architectural BIM authoring software (Autodesk 2019a). The BIM model was exported to an IFC file. The file content was visualized in a viewing software to verify its correctness and completeness for the selected use case (Solibri, 2019). In general, the IFC data exported from Revit Architectural was found to be complete and accurate. A limitation concerns the adjacency relationship between spaces, which is required to derive temperature differences between adjacent spaces. This relationship is not modeled explicitly in the IFC schema. It may be derived from second level space boundaries. However, corresponding second level space boundaries are not linked in the IFC file exported by Revit. Using clash detection algorithms in Solibri Model Checker (SMC) software, it is feasible to derive space adjacency relationships from an IFC model (Solibri, 2019). Unfortunately, it is currently infeasible to export semantically enriched IFC models from SMC. As an alternative, semantic enrichment of the BIM model was investigated using the Space Modeler (SM) system (Suter 2015). The SM system derives and exports the space adjacency relationship as well as other spatial relationships for a given building model. However, it is currently unable to process complete IFC files. As a workaround, the BIM model was exported from Revit in the DWG format. This lead to significant data loss and required data re-entry, e.g. of space geometry data. To summarize, the reuse and semantic enrichment of IFC models exported from a BIM authoring tool for the integrated model database is currently unresolved. A further issue is limited support for modeling space functions in Revit. Offices in the test building have different occupancy types, including team office, open plan office, and private office. Occupancy types were modeled as semantic labels and added to the BIM model using the SM system. The system was further used to define mentioned identifier mappings between BIM and BEMS objects.

In order to obtain a rudimentary list of available data points from the BEMS as well as to collect time series data, an Open Platform Communications (OPC) server was installed in the deployed Programmable Logic Controller (PLC). A script was used to read all 1906 OPC data items from this server. Another script reads and stores the current values from the server in a five minutes cycle. It turned out that extracting information about data point types, locations (references to devices), and units from the available data is challenging and laborious. First, there are many data points in the PLC which are not in use, meaning that the corresponding IO-ports are not wired. Therefore 1368 data points without any value change in four months were deleted from time series data. However, significant manual work is required to select the data items of interest. In this particular case, the only available information about each data point was a name which does not follow a consistent schema. Hence data point types, references to devices, as well as units had to be added manually.

A wireless data logging system was deployed in the test building to gain insights regarding the temperature, humidity and CO2 characteristics of individual offices. Due to its proprietary nature, data is exported from the system as CSV files that are imported into the time series database at regular intervals. Data collected by the system are verified by visualization in their spatial context. This is illustrated with a temperature data sample for the second floor of the test building (Figure 4). For the temperature data sample, the visualization reveals that most South-facing offices are overheating in the afternoon, while North-facing ones are in the comfort temperature range. The visualization supports the conclusion that the data sample is sensible.

Figure 4: Verification of dynamic data quality by visualization of a temperature data sample collected by data loggers on the second floor of the test building using the Space Modeler system (unit: ^oC).

6.4 Setup of integrated model database

For the integration of data from BIM and BEMS models, a container-based infrastructure was set up. Services for storage, interfaces, and security are provided in the form of Docker containers. Apache Jena components TDB (triple store) and Fuseki (SPARQL server) are used to store and provide the modeled semantic building information in a knowledge base. The time series database InfluxDB was installed to host time series data for available data points. High-level access to all this information is provided by a Representational State Transfer (REST) API implemented in ASP.NET Core. This allows users who are not familiar with semantic web technologies to gain data from the integrated model database without writing SPARQL queries.

The BIM model was converted to ifcOWL utilizing the Java-based IFCtoRDF tool. Subsequently, ontologies which are required to represent all aspects of BIM and BEMS models are loaded into the knowledge base. These are ifcOWL, Brick (Balaji, et al, 2016), BOT (Rasmussen et al, 2017), and QUDT (QUDT, 2019) for units. Mappings between these ontologies were defined and inserted in the triple store. An example for such a mapping is that an IfcSpace is a subclass of a space in BOT. Based on this mapping, a reasoner is able to assign the BOT space class to all IfcSpace instances. BOT models adjacency relations between spaces, which are not available in ifcOWL. In the following, locations of devices as well as relations between spaces, floors, and building parts were automatically extracted and inserted into the knowledge base from JSON-based outputs of the SM system which were generated in the BIM modeling phase. Finally, the semantically enriched list of data points created by the BEMS modeler was processed. While data points and their assignments to spaces and devices are represented in the knowledge base with concepts provided by the Brick ontology, units are taken from the QUDT ontology. An additional data property is used to specify the name of the corresponding time series in the time series database. Apart from the creation of the knowledge base, collected time series data of six months (February 2018 – June 2018) was imported into the InfluxDB.

The Autodesk Forge platform and Angular web application framework are used as a front-end for interactive, 3D visualization of the integrated building model (Autodesk, 2019b; Angular 2019). The front-end uses the REST API provided by the knowledge base to retrieve time series data from the integrated model database and visualizes them in their spatial context. This is illustrated in Figure 5 for a temperature data sample collected by data loggers in the test building.

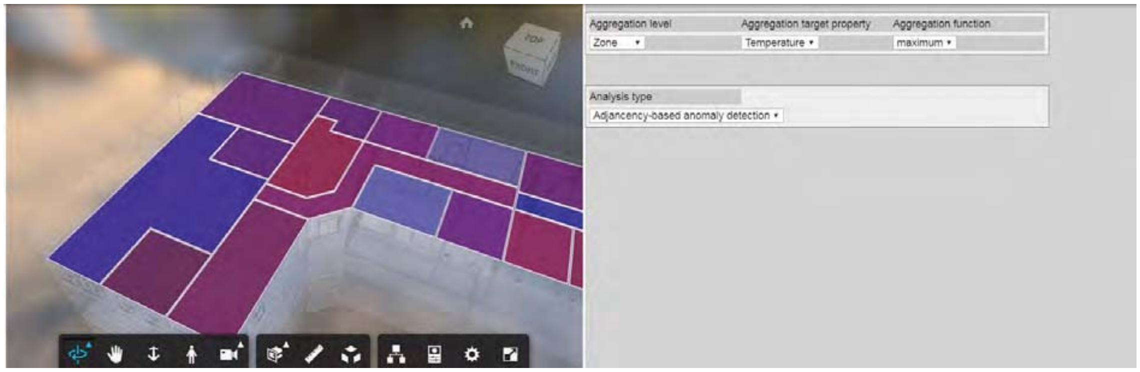
Aggregation level: Zone
Aggregation target property: Temperature
Aggregation function: maximum
Analysis type: Adjancency-based anomaly detection

Figure 5: Visualization of temperature data collected by data loggers on the second floor of the test building using the web based front-end application. Temperature data are aggregated at the room level (there may be several sensors in a room) based on maximum readings. Rooms are shaded to highlight those that are considerably hotter (red) or colder (blue) than their adjacent rooms.

6. Conclusion

The work presented in this paper is motivated by the need for improved reporting and visualization of energy and comfort related parameters in the building operation phase. Workflow models for setting up and maintaining an integrated model that supports such visualization and reporting have been proposed. Key tasks in the model setup workflow were tested for a medium-size office building. Several data modeling and processing challenges have been identified. They include incomplete as-is documentation of the BEMS and limited data interoperability. Specifically, the definition of mappings between BIM and BEMS objects that are modeled in different systems was labor-intensive. Automated extraction of semantic information from informal data point descriptions could address this issue. In future work, we plan to further test and evaluate model setup as well as maintenance workflows by deploying and using the integrated building model database in additional test buildings. A cost-benefit analysis will provide more detailed insights into the trade-offs between modeling effort and visualization and reporting capabilities enabled by the integrated building model. We will further investigate how routine model updates, such as the replacement of sensors or actuators, could be automated.

Acknowledgements

This work was funded under the project "Building Information Modeling for Building Energy Management Systems" (BIM4BEMS) by the FFG (Austrian Research Promotion Agency) program City of Tomorrow (project number 854677).

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