ObepME: An Online Building Energy Performance Monitoring and Evaluation Tool to Reduce Energy Performance Gaps

M. Jradi*, K. Arendt, F.C. Sangogboye, C.G. Mattera, E. Markoska, M.B. Kjærgaard, C.T. Veje, B.N. Jørgensen

Center for Energy Informatics, The Mærsk Mc-Kinney Moller Institute, University of Southern Denmark, 5230 Odense M, Denmark

* Corresponding author, Email: mjr@mmmi.sdu.dk

Phone: +4565508210; Address: Campusvej 55, DK-5230 Odense M, Denmark

Abstract

A major challenge facing the buildings sector is the absence of continuous commissioning and the lack of performance monitoring and evaluation leading to buildings energy performance gaps between predicted and actual measured performance. Aiming to better characterize, evaluate and bridge these gaps, the paper proposes an online building energy performance monitoring and evaluation tool ObepME, serving as a basis for fault detection and diagnostics and forming a backbone for continuous commissioning. A calibrated building dynamic energy model is developed and employed to automatically run on a daily basis and simulate the building transient performance for the previous day. The simulated energy consumption results form a baseline to which the actual collected data are compared to evaluate the dynamic energy performance gap. The OU44 university building in Denmark is considered as a case study to implement the proposed framework. A holistic energy model was developed in EnergyPlus and calibrated employing data from various building meters, collected weather conditions, generated occupancy schedules and systems operational parameters and set-points. The calibrated model was employed in the ObepME tool to automatically and continuously monitor and evaluate the OU44 building energy performance, on the level of the whole building and individual energy systems consumption, throughout the period from February to mid-March 2017. The reported dynamic energy performance gap was around -2.85%, -3.47% and 5.48% for heating, total electricity and ventilation system electricity consumption. In addition, specific observations were made on a daily basis in terms of the overall electricity, heating, lighting and ventilation energy consumption as highlighted by the ObepME tool. The ObepME tool is currently running automatically as a part of the OU44 building continuous commissioning and performance evaluation aiming to identify possible discrepancies and deviations paving the way for a methodical preventive fault detection and diagnostics process on various levels in the building.

Keywords: Performance gap, building energy, modelling and simulation, measured energy data, online performance monitoring, EnergyPlus.

1. INTRODUCTION

In order to increase the efficiency of the energy sector and reduce carbon dioxide emissions, having energy efficient buildings with low energy consumption is vital. However, optimism at the design stage and simply claiming that the building will use less energy compared to reference numbers doesn’t ensure that the building will consume less energy than expected and may only increase the energy performance gap. There is no straightforward definition of a performance gap in a building as no common standards and regulations define and characterize this gap. As broad definition, a building energy performance gap generally refers to the holistic mismatch between the predicted energy performance of a building and the actual measured performance at the site [1]. In overall, assessment of performance gaps in buildings is a part of the quality assurance with two major pillars: (1) a comprehensible and reliable baseline and (2) an accessible and comparable actual state. Such objectives and actual states are determined and derived from measurements, models, evaluations, comparisons and surveys [2].

Nowadays, a performance gap is more visible and characterized, having more sophisticated and accurate energy simulation tools along with automated meters and measuring devices. Moreover, considering the investments and resources allocated in terms of energy efficient building physical envelope and energy supply systems, customers and residents are expecting their houses and buildings to perform as expected at the design stage. In an effort to define and characterize energy performance gaps, Van Dronkelaar et al. [3] has highlighted three types of building performance gaps: a) a regulatory performance gap between predictions from compliance modeling tools and measured energy data; b) a static performance gap between predictions of performance simulation models and measured energy data; and c) a dynamic performance gap between results from calibrated dynamic performance models and measured energy data. However, they stated that with the large set of assumptions, generic and standard inputs and simple modeling and simulation methodologies, comparing predictions of the compliance modeling tools with actual measured energy doesn't provide a clear overview on the real energy performance gap in buildings. Currently, compliance modeling tools dominate the regulatory framework in EU countries. In terms of the regulatory performance gap, Van Dronkelaar et al. [3] reported an average gap of 34% between predicted and measured energy use in 62 case study buildings, with a standard deviation of 55%. The major factors along with their contribution to the large performance gap is as follows: building modeling (20-60%), occupants behavior (10-80%), and poor building operation (15-80%). They recommended to focus on the dynamic performance gap in buildings using calibrated dynamic models employing actual operating conditions and comparing the simulations to actual collected data for a better representation of the performance gap during the building operation phase. While causes of energy performance gaps in buildings are interrelated and connected, they could be divided and associated to the different building phases: design phase, construction phase, and operation phase as demonstrated in Table 1. [1,4,5]

Taking various causes of energy performance gaps in buildings into account, researchers have investigated frameworks, methodologies and solutions to bridge this gap. This includes improving the accuracy and modelling methodology of simulation tools at the design stage [6-10] in addition to addressing defects and quality issues that arise during the construction stage[11-14], and monitoring the occupants behavior [15-17] and understanding the impact of various components and systems during the operational and management phase[18-21]. In his investigation, De Wilde [1] reviewed the major root causes and the recent investigations in terms of energy performance gap between predicated and measured energy performance of buildings, proposing a classification of the gap based on the developed models and the developed comparison methods. He concluded that implementing a coordinated approach, combining model validation, improved data collection and accurate predictions and forecasts, is key in the future investigations to bridge the performance gap. Bordass et al. [22] investigated the energy performance gap in 16 non-domestic buildings in the period 1995-1999 and reported that the actual energy consumption exceeds the design numbers in most of the case study buildings in addition to highlighting major assumptions in the simulation tools which are not always valid in real cases. Similar conclusions were reported by Pegg et al. [23] who claimed that 80% of the investigated buildings consume more energy than expected including retail, education, office and residential buildings in the UK. Additional studies in Denmark and Italy have reported a performance gap up to 30% between the estimated and the actual energy consumption data [24-25]. Herrando et al. [26] conducted a study to assess the performance of 21 faculty academic and research buildings in Spain, comparing the actual data collected onsite to the estimated numbers by the Spanish official software for Energy Performance Certification of Buildings CALENER-GT. They reported an average discrepancy of 30%, associating this gap to the complex graphic implementation of buildings in the tool, generic operation schedules, generic materials and installations and standard operating conditions. In addition, Lehmann et al. [27] highlighted the importance of continuous monitoring of the energy performance of buildings, especially systems and components, in order to ensure that the building is operating as expected with minimal deviations. Ahn et al. [28] stated that instead of using standard and generic assumptions, accurate information regarding occupancy and occupancy behavior monitoring are key elements towards accurate building energy modeling and hence reducing the performance gap between simulation results and actual real-time data. Robinson et al. [5] focused on the building-user interaction and the influence of users behavior on the performance gap, and reported that the crucial challenges in this perspective are the conflicts between meeting the users demands and operating the building at the maximum energy efficiency mode. Frei et al. [2] investigated energy performance gaps in Swiss buildings and stressed that using static targets and limits is not feasible in the assessment of building performance, recommending the implementation of dynamic energy models and statistical approaches. Raftery et al. [29] highlighted that the feedback loop from measurements and actual data into predictions and simulations can improve the quality of future design models and provide better and realistic assumptions. In their study, Kampelis et al. [30] presented a comprehensive approach to evaluate the performance gaps in various industrial, residential and tertiary near-zero energy buildings. Three case study buildings were considered, comparing the design numbers against the buildings' real-time operation. The high performance gap reported was attributed to the limitations in the energy classification process in Italy and the lack of information on the actual occupancy schedules and activities. Although dynamic building models were developed for the three study cases, the authors used the models only as a basis for offline calibration using actual data from the sites and didn't employ the models in the continuous performance gap evaluation between the simulated building operation and the actual operation.

One of the major causes of the performance gap is the absence of continuous commissioning and the lack of feedback to designers, engineers, contractors and residents after building construction and handover, and thus missing valuable information in terms of the actual use of the building, actual systems operation and actual occupancy behavior [27]. Using smart metering and processing and interpreting data from the building real-time operation was found to be a useful input in reporting the overall aspects of building operation and aiding the decision making on implementing control and management operational strategies [31]. Regarding measurement meters, it was suggested that in addition to the overall energy consumption, sub-meters measurements and system-level meters are very useful to provide in-depth information regarding the performance gap [32]. Different researchers highlighted that the performance gap is lower when refined and calibrated energy models, using actual data, are used to simulate the building performance, considering various operational set points and dynamic schedules [2,3]. The background and review presented above draws special attention to the urgent need to reduce energy performance gaps in highly energy efficient buildings, highlighting the positive impact of continuous building commissioning and energy systems and occupancy behavior monitoring during the building operational phase along with the valuable added value provided by dynamic energy models in terms to predicting the building transient performance. In this context, this paper proposes an online building energy performance monitoring and evaluation tool (ObepME) to bridge the performance gap, as a part of building continuous commissioning, and serve as a basis for fault detection and diagnostics throughout the building operational and management phases. The paper builds up on the recent investigations aiming to reduce building energy performance gap with a proposed framework implemented and assessed considering a 2020 energy efficient case study building in Denmark. This is achieved through:

- Development of an automated online building energy performance monitoring and evaluation tool (ObepME) to monitor and assess building energy performance and ensure a proper operation, employing actual collected data and dynamic energy performance simulations.
- Continuous evaluation of the building dynamic energy performance gap employing the developed ObepME tool.
- Using the ObepME tool as a part of building continuous commissioning and as a basis for fault detection and diagnostics on different building energy supply systems.

2. CASE STUDY BUILDING

A case study of a highly energy efficient university teaching building in Denmark is considered in this work. The OU44 building, shown in Fig. 1, is located at the University of Southern Denmark Odense Campus and was opened for staff and students in November 2015. The 8500 m^2 building is mainly devoted to teaching with classrooms, meeting and seminar rooms and offices spreading along three floors with a full basement comprising of technical rooms, storage facility and installations. At the design phase, the plan was to have an energy efficient building complying with the Danish Building Low Energy Class 2015, however due to careful and well-organized planning, design and construction phases and the close collaboration between the Danish Building and Property Agency, contractors, university technical department and researches, it was shown during commissioning that the building complies with the highest building standard in Denmark, being one of the first and fewest public buildings in Denmark to comply with the future building class 2020 [33]. The overall period from design until building first operation was less than 13 months, delivering a highly energy efficient building from the physical envelope and the technical energy supply systems perspective and with no extra costs compared to other similar buildings. The building is established as a living energy lab with various research activities and projects, comprising highly efficient energy supply and management systems and technologies. In terms of energy supply systems, the building is fully connected to the district heating network to cover the heating demands with additional small electric boilers for domestic hot water. Radiators in various rooms are equipped with mechanical valves for operation management. In addition, the building has no cooling systems and rely solely on ventilation with four identical balanced-ventilation systems with air handling units of

35000 m^3/h nominal capacity each. The ventilation units serve the building four zones and are equipped with rotary thermal wheels for heat recovery. To compensate for the Danish cold weather, the ventilation systems comprise district heating-supplied heating coils to preheat the air before being delivered to the rooms. In addition, a solar photovoltaic system of 12 kW power capacity was installed on the building roof to deliver renewable energy-based electricity generation. To ensure a proper building operation from day 1, 11 technical performance tests were implemented in the building over three weeks at the commissioning stage, targeting building envelope and various energy supply systems including lighting, heating, electricity, ventilation, heat recovery unit, solar cells, and it was reported that the building complies with the building class 2020 strict requirements. In addition to the highly efficient energy supply systems, the building was loaded with a large number of meters and sensors on various levels and resolutions to allow full capability to monitor and control the building operation. Multiple meters were installed to measure consumption of electricity, heating, ventilation, lighting, plug loads, at the level of the whole building, floors, part of floor and certain test rooms. All building rooms are equipped with temperature, humidity, CO_2, PIR and illuminance sensors in addition to radiator valve position, ventilation damper position, blinds position and multiple temperature and pressure sensors along the energy supply scheme. In addition, a weather station is installed to record ambient temperature, wind speed and solar irradiation, and 17 cameras were installed at various building entrances and at different locations inside the building to monitor the occupancy behavior and report people counts. Moreover, the building is equipped with a Schneider Electric building management system (BMS) allowing control and optimization of the systems operation on the rooms and the whole building levels, where all sensors are accessible through a KNX bus, broadcasting records to the BMS based on the configuration. Data collected from the building are fetched from the BMS into a centralized database platform using Simple Measurement and Actuation Profile (sMAP) protocol, making it easier to be used for various applications including occupancy prediction and model calibration and comparison.

3. REGULATORY PERFORMANCE GAP

In this section, we will evaluate the building energy performance gap from the regulatory performance gap perspective. As mentioned earlier, the building regulatory energy performance gap highlights the mismatch between the compliance modelling tools predictions at the design stage and the reported measured data from the site. While researchers have studied energy performance gap in various resolutions, the majority of studies have focused on the building annual energy consumption being the key factor in assessing regulatory performance gap [34]. In this study, we will also consider the overall annual energy consumption as a factor for performance gap assessment in addition to the energy consumption breakdown into heating, electricity, lighting and ventilation consumption. BE10 is the official compliance tool for building energy performance in Denmark [35]. While considering different aspects of the Danish Building Regulations, the tool allows simple and fast monthly estimations for the building energy consumption employing a static simplified modeling and simulation approach with major assumptions. Such assumptions include considering the whole building as one large thermal zone, adopting generic and standard fixed schedules for plug loads, lighting, ventilation flow rates and heating set points, and most importantly neglecting the impact of weather conditions and occupancy behavior and activities with constant ambient design temperature and generic fixed occupancy schedules. To comply with the 2020 Danish building energy class, the OU44 building maximum allowed annual primary energy consumption is around 42 kWh//m^2, as predicted by the BE10 tool considering the building type, size, envelope, systems and various use aspects. To evaluate the regulatory energy performance gap, Fig. 2 depicts the measured monthly consumption for lighting, ventilation and heating in 2016 against monthly predictions by the design tool BE10. Comparing the design energy consumption predictions and the actual measured numbers shows a clear mismatch where the design tool generally underestimates the lighting and heating consumption and overestimates the ventilation units electricity consumption. Thus the estimated annual regulatory performance gap of the OU44 building is around 27.2% for heating, -122.3% for ventilation electricity and 64% for lighting with the measured data as a reference. This large mismatch between the design and measured numbers are predominantly due to the BE10 tool large number of assumptions and uncertainties. As an example, while the ventilation system is majorly CO_2 level-driven and where July month is in general a vacation month and very few people are using the building, it can be noticed that the measured ventilation electricity consumption in July attains a yearly minimum where BE10 design tool predicts a yearly maximum consumption in this month.

4. DYNAMIC PERFORMANCE GAP

The results shown in the previous section in terms of the large mismatch between the design numbers and the actual measured data from the OU44 building are in line with findings of Frei et al. [2] and Van Dronkelaar et al. [3]. Both studies highlighted that with the large assumptions and uncertainties of compliance tools employed in the majority of European countries, the regulatory gap doesn't provide a useful and feasible evaluation for the real building energy performance gap. They prioritized the need for more comprehensive dynamic models which are calibrated using actual collected operational parameters and data to provide better evaluation and prediction of the overall building performance. Thus, this section will focus on evaluating the dynamic energy performance gap of the OU44 building employing a detailed dynamic energy simulation model and measurements and data collected from the site. To aid this process, an online building energy performance monitoring and evaluation tool (ObepME) is proposed and developed allowing automatic online monitoring of the building systems energy performance and identifying possible performance discrepancy and deviation paving the way for a methodical and preventive fault detection and diagnostics process. The overall online performance monitoring and evaluation methodology is shown in Fig. 3, comprising the following steps:

- A building 3D model is developed using information regarding the geometry, orientation and zones distribution.
- Building envelope and systems design specifications along with the 3D developed model are used to develop the building dynamic energy performance model.
- Weather conditions data collected onsite, occupancy schedules generated using input from camera counts, energy systems operational parameters and set points and data collected from building meters are used to calibrate the developed energy model.
- The calibrated dynamic energy model and the data obtained from various meters around the building are the two pillars of the online performance monitoring and evaluation tool where simulations from the energy model and real data from the building are compared and demonstrated in a dashboard platform developed.
- If a performance gap is reported, the overall process of fault detection and diagnostics is launched aiming to identify any faults or underperformance issues regarding the different building energy supply systems.
- If faults are detected, an alarm is highlighted for systems repair and maintenance. Otherwise, if no faults are identified, then the dynamic energy performance model is re-calibrated using updated occupancy schedules, weather conditions and operational parameters and setpoints.

It shall be mentioned that the fault detection and diagnostics methodology is not included in this study, but it is a part of the overall framework of COORDICY project aiming to improve the energy performance of newly built buildings and reduce the associated performance gaps [36]. Thus the results and feedback from the ObepME tool will serve as an input and basis to aid the fault detection and diagnostics process.

4.1. Dynamic Energy Performance Model Development

Having a holistic detailed and dynamic energy model is key to accurately simulate the building energy performance taking into account various building characteristics and specific properties including building type and location, weather conditions, orientation and geometry, thermal envelope properties, building use, energy systems, building services, occupancy behavior and schedules and various loads. In this study, EnergyPlus is used as a basis for the holistic building energy modeling and simulation, being a free, well-established and validated tool with powerful capabilities in simulating the detailed and accurate building operation and large flexibility in communicating with other tools [37]. EnergyPlus modeling and simulation methodology is based on a nodal approach, solving heat and moisture transport equations, with each zone having homogeneous volume and uniform state variables. To aid the energy modeling and simulation procedure, two supporting tools are employed in this work, Sketchup Pro and OpenStudio. Sketchup Pro is a 3D modeling software allowing detailed and accurate representation of the building 3D model defining various spaces and taking into account orientations, geometries and different building zones. In addition, OpenStudio is a cross-platform collection of software tool to aid energy modeling and simulation using EnergyPlus engine. The tool allows linking the 3D building model developed in Sketchup Pro with the EnergyPlus engine through a flexible and user-friendly modeling interface. In overall, OpenStudio is used to define various building specifications and characteristics including thermal envelope, energy systems, loads and schedules. The holistic whole building energy modeling and simulation methodology is presented in details by Jradi et al. [38]. To generate the building 3D model, a Building Information Model developed by the consultant for the OU44 building was investigated and assessed. However, as the model was not developed with the aim to be used for energy simulation, it didn't provide any added value and a whole building 3D model was developed in Sketchup Pro as shown in Fig. 4, taking into account orientations and geometry and representing various building spaces. Building up on the developed 3D model, the holistic dynamic energy model for the OU44 building was developed taking into account various design information in terms of building specifications and characteristics. The holistic building model developed has 190 thermal zones, spanning across three floors and a basement, with a district heating loop for heating supply and 4 ventilation units with heat recovery wheels and preheating loops as implemented in the actual building. A screenshot from the OpenStudio model is presented in Fig. 5.

4.2. Occupancy Counts and Schedules Generation

Tracking the building occupants' behavior and activities and having accurate occupancy schedules through detailed estimation of the number of people is key to understand, characterize, simulate and optimize the energy performance of buildings along with thermal comfort and indoor air quality predictions. Yang et al. [39] analyzed actual energy consumption data from an institutional building to investigate the factors that mostly influence the discrepancy between real energy consumption and model simulations or predictions, and they reported that occupancy behavior and accurate schedules are of highest importance. To estimate occupancy counts in buildings, most energy simulation models and HVAC control systems of commercial buildings assume standard maximum occupancy numbers during working hours [40]. Erickson et al. [40] investigated the impact of occupancy estimates on the energy performance of buildings by comparing actual occupancy estimates obtained from 16 nodes camera sensor with standard maximum occupancy count estimates. They showed that the optimization strategies employing real time occupancy data allow about 42% annual energy savings compared to the current state of the art baseline strategy. Other sensor modalities such as CO_2, WiFi access points and PIR have been investigated for obtaining occupancy count estimates, however these sensors are accompanied by several issues and challenges and hence yield estimates with high RMSE [40,41]. Considering various sensor modalities highlighted in the literature, thermal and 3D stereovision cameras are highlighted as an optimal solution for people count estimations providing minimal errors. However, the relatively higher cost of thermal cameras compared to the 3D stereovision ones makes the latter a more convenient and economically feasible fit for occupancy count estimations.

In this context, 17 stereovision cameras were implemented in the OU44 Building case study, located at all building entrances, all passages between floors and at the entrances of 4 selected rooms. Fig. 6 shows the 3D stereovision camera unit and a sample image produced by the camera. Using these 3D stereovision cameras, the building users and occupants privacy rights are protected as the video processing is performed real-time in the camera unit itself and only the number of people and the estimation counts are reported. In terms of people counts accuracy, the cameras are mostly accurate on the short term where some errors may occur on the long term due to error accumulation and thus yielding inaccurate people counts or negative values. Major issues that may accompany people counts using 3D stereovision cameras are pixel intensity fluctuation, occlusion and poor lighting conditions. Aiming to correct the erroneous counts that may be reported by the cameras, occupancy count problems are first formulated through highlighting transition events from different count lines and computing the total transition and the cumulative count in the building at each timestamp. Then a probabilistic correction method (PLCount) [41] is employed to cure and correct the computed transition and corresponding cumulative people counts following three steps: (1) Initialize a probability and propagation matrix; (2) Calculate the elements in the probability and propagation matrix; and (3) Calculate new count estimates by backtracking the propagation matrix. Fig. 7 shows erroneous counts from the 3D cameras and the corresponding corrected occupancy counts employing the mentioned correction methodology. Thus, using the occupancy counts from the different 3D cameras around the building, updated building occupancy schedules are generated on an hourly basis. The weekly profile for each month is computed by estimating the average reported occupancy counts for each day in the week for that corresponding month. Thus, the obtained averages are propagated for all days to form a week profile for each month, leading to the generation of occupancy profiles within a flexible and robust platform and with full capability of seamless data queries of aggregated people counts.

4.3. Dynamic Model Calibration

The dynamic building energy performance model developed in OpenStudio will be used to simulate the transient behavior of the OU44 building, predicting the holistic energy performance of the building and used as a basis to evaluate the dynamic building energy performance gap. However, as recommended by Van Dronkelaar et al. [3], calibrated dynamic building energy models under real weather conditions and using actual operating conditions and occupancy patterns provide a better evaluation and characterization of the dynamic performance gap during the building operation phase. Thus, the detailed holistic OU44 building energy model will be calibrated for the period from September to December 2016, employing weather data collected from the weather station at the building roof in addition to updated occupancy schedule based on the camera counts around the building and employing operational set points and parameters from the building management system. Fig. 8 presents the reported measured weather conditions in the period from September to December 2016, showing solar radiation, wind speed and outdoor dry bulb air temperature. Moreover, to aid the developed dynamic model calibration process, occupancy counts from the different 3D stereovision cameras around the building are collected in the period from September to December 2016 and occupancy profiles were generated to be employed in the simulation engine. Additional information regarding energy systems set points and operational parameters including heating system, ventilation units and heat recovery units are introduced as inputs to the dynamic energy performance model.

As updated weather data, occupancy profiles and operational parameters are introduced to the dynamic model, the holistic OU44 building model is calibrated employing the methodology developed by Hale et al. [42], loading measured monthly utility bill data into the baseline model and varying different parameters within the model over multiple iterations. As Hale et al. [42] calibrated the model only against the overall monthly energy consumption in the building, we have opted to calibrate the OU44 model not only on the level of the whole building consumption but also employing ventilation, lighting and heating systems individual monthly consumption. Using the OpenStudio Parametric Analysis Tool and the Building Component Library (BCL) measures, multiple parallel simulations were performed for various scenarios and the one with the lowest deviation compared to the measured lighting, ventilation and heating consumption data is selected. The most influential parameters in calibrating the dynamic energy performance model include infiltration rates, equipment and electrical devices efficiency, ventilation rates and operation schedules. Fig. 9 depicts the overall energy performance of the OU44 building from September to December as predicted by the calibrated dynamic EnergyPlus model. In addition, the figure compares the simulated energy consumption for heating, lighting and ventilation with the design numbers of BE10 and the actual measured energy consumption from the building energy meters. Considering the significant gap between the BE10 numbers and the actual measured energy data, it is shown that the calibrated dynamic energy performance model predicts more accurately the energy consumption with lower deviation compared to the Danish building certification static tool BE10. Comparing the simulated monthly energy data and the actual measured data, Table 2. reports a maximum deviation of -8.4%, -6.9% and 3.9% in terms of heating, ventilation electricity and lighting consumption respectively. As mentioned above, this calibrated dynamic performance model will be employed as a basis to run within the Online Energy Performance Monitoring Tool to automatically simulate the daily energy performance of the OU44 building and estimate building dynamic performance gap, compared to the reported actual building energy data.

4.4. Online Energy Performance Monitoring and Evaluation Tool

In order to continuously monitor and evaluate the OU44 building energy performance, an online energy performance monitoring and evaluation tool (ObepME) is developed in this study, having the simulations from the calibrated dynamic energy performance model and the actual measured energy consumption data as two key pillars. The ObepME tool aims to ensure that the building is performing and operated in the most efficient manner and to reduce the dynamic energy performance gap through automatic comparison between the simulations from the dynamic energy performance model and the measured data from the different meter streams in the building. The calibrated detailed EnergyPlus model presented in the previous sections is employed to automatically run on a daily basis to simulate the building transient performance for the previous day taking into account measured weather conditions, occupancy counts from the stereoscopic cameras located at different building entrances, and inputs from the building management system in terms of energy systems' operational parameters and set-points. The dynamic model developed in EnergyPlus is characterized with an IDF file providing a detailed definition for the different aspects of the building model including envelope, systems, schedules and loads. The EnergyPlus model is incorporated into the ObepME tool using Functional Mock-Up Interface (FMI) [43], which is an open co-simulation protocol enabling to connect models developed in different modeling and simulation environments with each other or with third-party software. The EnergyPlus model is exported to a Functional Mock-Up Unit (FMU), a single self-contained file which can be run by any FMI-compatible framework, using the EnergyPlusToFMU tool [44]. The model is prepared for the export by exposing selected input/output variables (room temperatures and CO_2 levels, temperature and CO_2

setpoints, etc.) in the interface. This step is automated with EPQuery tool [45], which enable modifying EnergyPlus IDF files using Python scripts. The variables are then mapped to the data streams from the data storage platform collecting measurements from streams at different levels in the building. Through using FMI, ObepME is completely model-agnostic and only expects an FMU and the mapping of variables to data streams. It is therefore easy to update the model during the operation of the tool, change the simulation engine or deploy the tool to another building for which an FMI-compliant model is available.

The EnergyPlus platform provides weather files for different locations as weather conditions recorded from multiple years are merged in an aggregate weather file that represents a Typical Meteorological Year [46]. Since this aggregate file aims to be representative for a standard year, the actual weather conditions will generally have different patterns and may considerably differ from the typical year conditions. Moreover, the available EnergyPlus weather file for the closest location is for Copenhagen, which is more than 150 km away. Therefore, this weather file is used as a basis and is updated using actual weather conditions measured onsite. One of the limitations of the FMU export in EnergyPlus is that the variables that can be exposed in the interface are limited to output variables, schedules and actuators [44]. The weather variables cannot be exposed in the interface and the weather file is included inside the FMU. Since it is necessary for the ObepME tool to automatically update the weather data each day, the tool unpacks the FMU, which is internally a ZIP file with a model DLL file and resources, including weather data, and overwrites the weather file with new measurements. The measured weather data is retrieved from the weather station located on the roof of the building allowing collecting real-time measurements of solar radiation, wind speed and ambient dry-bulb temperature. Other weather variables required by EnergyPlus are based on Typical Meteorological Year provided by the DOE weather files, including the relative humidity, total and opaque sky cover, illuminance and atmospheric pressure.

While the building energy performance for the previous day is automatically simulated and reported on a daily basis, the simulation results are used as a baseline and compared to the measured energy consumption data from the building to evaluate the dynamic energy performance gap. As the building is loaded with multiple energy meters on different levels of aggregation, the performance of the building is not only reported in terms of the whole energy performance consumption but also on the level of different individual energy systems operation including ventilation units, lighting system, heating system and electricity, in order to provide a clearer overview regarding the performance gap on the level of the whole building as well as the level of the individual energy systems. To aid data visualization, comparison and analysis, a dashboard application was developed. The dashboard platform is specific to the case study building, allowing reporting and monitoring different measured data streams collected from meters around the building in addition to reporting the simulation results of the dynamic energy performance model. The dashboard application is used for:

- Visualization of the data from both dynamic building model simulations and meter measured data streams. As the building is loaded with numerous sensors and meters, the visual representation of the harvested actual data is a relevant aspect. Prior to the display, the raw data is smoothed and cleaned from outliers and missing data.

- Comparison of the actual building energy performance with the simulated performance in terms of the whole building energy consumption and individual energy systems operation. The comparison highlights the deviation in the energy performance of the building compared to an expected performance level and thus reporting the building dynamic energy performance gap in the investigation period.

Fig. 10 presents the interface of the dashboard application in the mode of visualization of the energy data streams from the ventilation electricity consumption for one of the ventilation units in the building. The graph shows both the actual data as well as the predicted data.

4.5. Results and Discussion

The online building energy performance monitoring and evaluation tool developed in this study was implemented and tested to monitor the OU44 building energy performance throughout the period spanning from the beginning of February to mid-March 2017. The generated occupancy profile along with the collected conditions and energy systems set-points from the building management system are introduced as inputs to the dynamic energy performance model allowing the automatic online daily building energy performance simulation. The simulated energy consumption results are compared online with the measured daily energy consumption data collected from the energy meters around the building. The OU44 building energy performance is monitored and reported not only in terms of the whole building overall heating and electricity consumption, but also on the level of different individual energy systems including the lighting system and four ventilation units serving the building zones. This will allow a more detailed and clear overview on the individual systems operation and performance gap. Table 3 summarizes the OU44 building energy consumption as predicted by the calibrated EnergyPlus model for the investigated period, along with the measured data from the building meters. In comparison to the simulations baseline, the dynamic energy performance gap of the building in the investigated period is around -2.85% for heating, -3.47% for total electricity, -1.25% for lighting and an average of 5.48% for ventilation system electricity consumption.

Figures 11 and 12 present the simulated daily energy consumption for heating and lighting respectively along with the actual consumption reported by the meters around the building. In addition, Fig. 13 provides an overview showing the simulated daily electricity consumption of the four ventilation units in the building as well as the measured daily consumption from the site. The dynamic energy performance gap in terms of heating, electricity, lighting and ventilation is presented in Fig. 14 for the data reported by the online building energy performance monitoring and evaluation tool during the period of study. The two figures 14.(a) and 14.(b) allow monitoring and tracking the daily energy performance gap as reported by the online monitoring tool to assess the actual energy performance compared to the expected simulated energy performance baseline on the level of the whole building as well as the individual energy systems. In Fig. 14, a negative gap means that the building or the energy system is consuming less energy compared to the expected baseline where a reported positive gap implies that the building/energy system' actual energy consumption exceeds the expected simulated baseline.

Based on the current investigation of the building energy performance in the studied period, the following overall observations can be derived in terms of high energy consumption:

- Relatively high electricity consumption of Ventilation Unit 1 in the weekdays from Feb 1 to Feb 16
- Relatively high electricity consumption of Ventilation Units 2, 3 and 4 in the weekdays within the period from Feb 26 to Mar 14
- High heating consumption in the first week of February
- High lighting consumption in the third and fourth weekend of February
- High heating consumption in the period from 7 to 10 March.

Moreover, specific observations could be made on a daily basis in terms of the overall electricity, heating, lighting and ventilation energy consumption as highlighted by the ObepME tool. Concentrating on the positive performance gap (where actual consumption is higher than the expected simulation numbers), and if an acceptable performance gap within 20% is assumed, then it is shown that the heating and lighting consumption exceeds the limit in 4 and 3 days respectively within the investigated period. In terms of the ventilation units, Ventilation Unit 4 electricity consumption exceeds the limit in 3 days with each of the other units exceeding the limit in only one day within the reported period. Based on the illustrated overall building continuous commissioning framework using ObepME tool, these observations are introduced as input to the fault detection and diagnostics methodology to investigate and assess the possibility of having faulty or underperforming components within the energy supply systems. This feedback from the ObepME tool will help the building operators to identify faults as soon as they occur and thus will allow saving time and resources in terms of energy supply systems maintenance and repair. Moreover, the systems operation strategies, in the days when those performance gap observations are reported, shall be reviewed and assessed to ensure a proper energy management pattern. In addition to the consumption variables reported in this study, the tool reports as well the performance gap in terms of individual lighting and heating meters per building sections. In overall, it could be concluded that the OU44 building overall energy performance throughout the period extending from the beginning of February to mid-March is to a large extent following a proper operation pattern, where the dynamic performance gap is in overall within a certain level of acceptance.

The ObepME tool is currently set up and running automatically as a part of the OU44 building continuous commissioning and performance evaluation. The tool will continuously monitor the overall building performance and the energy systems operation, comparing online daily dynamic energy performance simulations and actual data from various meters in the building. As a result, the dynamic energy performance gap is reported and evaluated to ensure a proper operation of the building compared to a simulated baseline. This will highlight any discrepancies in the performance and detect unusual behavior, particularly on the individual energy systems level, paving the way for a comprehensive and methodical preventive fault detection and diagnostics process on various levels in the building. Moreover, different indicators may be derived by sliding integration of the gap over different integration periods to identify levels of discriminators and sort out random fluctuations from systematic errors which may be indicative of system or faults. In addition to the major role in energy performance monitoring and evaluation as part of the building continuous commissioning process, combining real-time measurements and dynamic energy performance simulations from the EnergyPlus calibrated model is beneficial in improving the overall efficiency and operation of various energy supply systems, allowing the development and implementation of more comprehensive and effective operation management and control strategies. This was demonstrated by Li et al. [47], where a case study of Sutardja Dai Hall at the University of California - Berkeley was considered. The actual energy consumption measurements were used to calibrate the EnergyPlus dynamic energy performance model, which was used to implement and test various energy efficient measures and demand response events in addition to operation scenarios of different energy supply systems including heating, cooling and lighting systems. Moreover, the developed white-box model can be potentially used in an on-line model predictive control framework, as shown in Henze et al. [48] and in May-Ostendorp et al. [49]. Alternatively, the model results can be used to train low-order or statistical models, especially for zones and components without sufficient measured data, as in the procedure presented by Prívara et al. [50]. This work is carried out under the international research project COORDICY: "ICT-driven Coordination for Reaching 2020 Energy Efficiency Goals in Public and Commercial Buildings" [51]. The project is an interdisciplinary collaboration research platform with more than 20 academic institutions and industrial partners in Denmark and the US, aiming to advance ICT-driven research and innovation in improving energy efficiency of public and commercial buildings. The case study considered, OU44 university building, is one of the major case study buildings for investigation under COORDICY project, with the aim to implement the developed framework in the other case study buildings.

5. CONCLUSION

With a major contribution to the overall energy consumption and the corresponding greenhouse gas emissions, improving the building sector efficiency and performance has been prioritized by the EU to meet the ambitious 2020 and 2050 energy and climate objectives and enhance energy security and energy supply stability. Significant efforts have been made and concentrated on enhancing the energy performance of the building stock through improving the quality and efficiency of various components and energy supply systems, increasing renewable and alternative energy resources share and developing advanced operation management and control strategies. However, one of the main challenges facing the building stock, especially newly built energy efficient buildings, is the absence of continuous building commissioning and the lack of performance monitoring and evaluation leading to a building energy performance gap characterized by the holistic mismatch between the predicted and the actual measured energy performance. In this study, an online building energy performance monitoring and evaluation tool ObepME is proposed to better characterize, evaluate and bridge energy performance gaps in buildings. The tool is intended to serve as a basis for fault detection and diagnostics throughout the building operational and management phase in addition to forming a backbone for the building continuous commissioning and performance evaluation. An overall dynamic building energy performance model is developed and calibrated to be used as a part of the ObepME tool to automatically and continuously run on a daily basis to simulate the building transient performance for the previous day considering measured climatic conditions, estimations of occupancy counts, and various energy systems' operational parameters and set-points fed as input from the building management system. Thus, the dynamic energy performance gap is evaluated being the difference between the actual measured energy consumption data from meters and the simulated energy consumption results being the baseline for operation. To aid data visualization, comparison and analysis, a dashboard application was developed. The proposed framework is implemented and assessed considering a case study of the OU44 University building in Denmark. The building complies with the future Danish building class 2020, and is loaded with a large number of meters and sensors on various levels in addition to weather station on the building roof and 17 stereoscopic cameras located at different building entrances to count and estimate occupancy.

First, the building regulatory energy performance gap is calculated, comparing measured monthly consumption data for lighting, ventilation and heating in 2016 against monthly predictions by the design certification tool BE10. The estimated annual regulatory performance gap was found to be about 27.2%, -122.3% and 64% for heating, ventilation electricity, and lighting. The respectively large regulatory performance gap reported is primarily due to the BE10 tool large number of assumptions and uncertainties in the modeling methodology and model inputs. To provide a better and more comprehensive characterization and representation of energy performance gaps in buildings, the developed ObepME tool is implemented in the case of the OU44 building to automatically and continuously evaluate the dynamic energy performance gap with the capability to monitor and evaluate the energy performance of the building. A holistic dynamic energy performance model was developed in EnergyPlus considering various building specifications, and was calibrated in the period from September to December 2016, employing data from various building meters, collected weather conditions, generated occupancy schedules and energy systems operational parameters and set points. The calibrated model was found to predict well the energy consumption of the building with a maximum deviation of -8.4%, -6.9% and 3.9% in terms of heating, ventilation and lighting consumption. The calibrated detailed model was used as a part of the ObepME tool to automatically and continuously monitor and evaluate the OU44 building energy performance, on the level of the whole building and individual energy systems consumption, in the period spanning from February to mid-March 2017. The evaluated building overall dynamic energy performance gap was about -2.85% for heating, -3.47% for total electricity, -1.25% for lighting and 5.48% for ventilation system electricity consumption. Moreover, through monitoring the building performance and energy consumption on a daily basis, the ObepME tool allows deriving specific observations regarding the daily performance of the individual energy supply systems and highlighting periods with relatively high energy consumption. The developed ObepME tool is currently implemented as a part of the continuous building commissioning process, running and reporting the daily overall energy consumption on the whole building level and on the level of the individual energy supply systems. In addition, the tool will allow the derivation of various indicators by sliding integration of the gap over different periods to identify levels of discriminators and differentiate random fluctuations from systematic errors which may be indicative of system faults. The overall framework will provide a full capability to monitor various aspects of the OU44 building performance and identify possibly deviations and discrepancies, paving the way for a systematic and methodical preventive fault detection and diagnostics process on various building components and systems levels.

ACKNOWLEDGEMENT

This work was carried out under COORDICY Project, funded by Innovation Fund Denmark, ID number: 4106-00003B.

REFERENCES

1. P. de Wilde, The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction 41 (2014) 40-49.
2. B. Frei, C. Sagerschnig, D. Gyalistras, Performance gaps in Swiss buildings: an analysis of conflicting objectives and mitigation strategies, Energy Procedia 122 (2017) 421-426.
3. C. van Dronkelaar, M. Dowson, E. Burman, C. Spataru, D. Mumovic, A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings, Frontiers in Mechanical Engineering 1 (2016) 17.
4. A.C. Menezes, A. Cripps, D. Bouchlaghem, R. Buswell, Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap, Applied Energy 97 (2012) 355-364.
5. J.F. Robinson, T.J. Foxon, P.G. Taylor, Performance Gap Analysis Case Study of a Non-Domestic Building, Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 169 (2016) 31-38.
6. L. Jankovic, A method for reducing simulation performance gap using Fourier filtering, Proceedings of Building Simulation 2013: 13th Conference of International Building Performance Simulation Association, Chambery, 26-28 August 2013.
7. P. André, B. Georges, J. Lebrun, V. Lemort, From model validation to production of reference simulations: how to increase reliability and applicability of building and HVAC simulation models, Building Services Engineering Research and Technology 29 (2008) 61-72.
8. S. Habibi, The promise of BIM for improving building performance, Energy and Buildings 153 (2017) 525-548.
9. O. Oduyemi, M. Okoroh, Building performance modelling for sustainable building design, International Journal of Sustainable Built Environment 5 (2016) 461-469.

10. L.C. Ng, A.K. Persily, S.J. Emmerich, Improving infiltration modeling in commercial building energy models, Energy and Buildings 88 (2015) 316-323.
11. M. Hienonen, I. Raina, E. Tackett, T. Kauppinen, The Importance of Building Physics in Improving the Quality Control of Buildings – The Role of Public Authority, Energy Procedia 132 (2017) 99-104.
12. M. Bell, J. Wingfield, D. Miles-Shenton, J. Seavers, J. Low carbon housing: lessons from Elm Tree Mews, Joseph Rowntree Foundation. M. Bell, J. Wingfield, D. Miles-Shenton, J. Seavers, Low Carbon Housing: Lessons from Elm Tree Mews, Joseph Rowntree Foundation, York (2010).
13. M. Buitrago, J.M. Adam, Y.A. Alvarado, J.J. Moragues, I. Gasch, P.A.Calderón, Designing construction processes in buildings by heuristic optimization, Engineering Structures 111 (2016) 1-10.
14. H. Shim, G. Choi, Study of construction convergence technology for performance improvement in functional building materials, Journal of Building Engineering 11 (2017) 108-114.
15. S. Wei, R. Jones, P. de Wilde, Driving factors for occupant-controlled space heating in residential buildings. Energy and Buildings 70 (2014) 36-44.
16. T. Ekwevugbe, N. Brown, V. Pakka, D. Fan, Improved occupancy monitoring in non-domestic buildings, Sustainable Cities and Society 30 (2017) 97-107.
17. Z. Yu, F. Haghighat, B. Fung, E. Morofsky, H. Yoshino, A methodology for identifying and improving occupant behaviour in residential buildings, Energy 36 (2011) 6596-6608.
18. A.H.Oti, E. Kurul, F. Cheung, J.H.M.Tah, A framework for the utilization of Building Management System data in building information models for building design and operation, Automation in Construction 72 (2016) 195-210.
19. A. Dasgupta, A. Prodromou, D. Mumovic, Operational versus designed performance of low carbon schools in England: bridging a credibility gap, HVAC&R Research 18 (2012) 37-50.
20. M. Safa, M. Safa, J. Allen, A. Shahi, C.T.Haas, Improving sustainable office building operation by using historical data and linear models to predict energy usage, Sustainable Cities and Society 29 (2017) 107-117.
21. M. Molina-Solana, M. Ros, M.D. Ruiz, J. Gómez-Romero, M.J. Martin-Bautista,Data science for building energy management: A review, Renewable and Sustainable Energy Reviews 70 (2017) 598-609.
22. B. Bordass, R. Cohen, M. Standeven, A. Leaman, Assessing building performance in use 3: energy performance of probe buildings, Building Research & Information 29 (2001) 114-128.
23. I.M. Pegg, A. Cripps, M. Kolokotroni, Post-occupancy performance of five low-energy schools in the UK, ASHRAE Transactions 113 (2007) 3-13.
24. S. Petersen, C.A. Hviid, The European energy performance of buildings directive: comparison of calculated and actual energy use in a Danish office building, Proceedings of IBPSA-England first building simulation and optimisation conference (BSO 2012), Loughborough (2012).
25. L. Tronchin, K. Fabbri, A Round Robin Test for buildings energy performance in Italy, Energy and Buildings 42 (2010) 1862-1877.
26. M. Herrando, D. Cambra, M. Navarro, L. Cruz, G. Millán, I. Zabalza, Energy Performance Certification of Faculty Buildings in Spain: the gap between estimated and real energy consumption, Energy Conversion and Management 125 (2016) 141-153.
27. U. Lehmann, J. Khoury, M. K.Patel, Actual energy performance of student housing: case study, benchmarking and performance gap analysis, Energy Procedia 122 (2017) 163-168.
28. K.U. Ahn, D.W. Kim, C.S. Park, P. de Wilde, Predictability of occupant presence and performance gap in building energy simulation, Applied Energy 208 (2017) 1639-1652.
29. P. Raftery, M. Keane, J. O'Donnell, Calibrating whole building energy models: an evidence-based methodology, Energy and Buildings 43 (2011) 2356-2364.
30. N. Kampelis, K. Gobakis, V. Vagias, D. Kolokotsa, L. Standardi, D. Isidori, C. Cristalli, F.M. Montagnino, F. Paredes, P. Muratore, L. Venezia, M.K. Dracou, A. Montenon, A. Pyrgou, T. Karlessi, M. Santamouris, Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings, Energy and Buildings 148 (2017) 58-73.
31. D. Kolokotsa, The role of smart grids in the building sector, Energy and Buildings 116 (2016) 703-708.

32. G. Newsham, B. Birt, C. Arsenault, L. Thompson, J. Veitch, S. Mancini, A. Galasiu, I. Macdonald, G. Burns, Do green buildings outperform conventional buildings? Indoor Environment and energy performance in North American offices (Report RR-329), Natural Research Council Canada (2012).
33. University of Southern Denmark, Building 44, Bygningsstyrelsen. Available from: https://www.bygst.dk/godt-byggeri/performancetest/cases/syddansk-universitet,-bygning-44/?AspxAutoDetectCookieSupport=1
34. E.H. Borgstein, R. Lamberts, J.L.M. Hensen, Evaluating energy performance in non-domestic buildings: a review, Energy and Buildings 128 (2016) 734-755.
35. BR10 Danish Building Regulations. Available from: http://bygningsreglementet.dk/file/155699/BR10_ENGLISH.pdf
36. B.N. Jørgensen, M.B. Kjærgaard, S. Lazarova-Molnar, H.R. Shaker, C.T. Veje, Challenge: Advancing energy informatics to enable assessable improvements of energy performance in buildings. Proceedings of the 6th ACM International Conference on Future Energy Systems, Bangalore, India, 2015, pp. 77-82.
37. EnergyPlus, whole building energy simulation program. Available from: https://energyplus.net/
38. M. Jradi, C. Veje, B.N Jørgensen, Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach, Energy and Buildings 151 (2017) 306-319.
39. J.J. Yang, M. Santamouris, S.E. Lee, C. Deb, Energy performance model development and occupancy number identification of institutional buildings. Energy and Buildings, 123 (2016) 192-204.
40. V.L. Erickson, M.A. Carreira-Perpinan, A.E. Cerpa, OBSERVE: occupancy-based system for efficient reduction of HVAC energy, Proceedings of IEEE 10th International Conference on Information Processing in Sensor Networks (IPSN) (2011), pp. 258-269.
41. F.C. Sangogboye, M.B. Kjærgaard, PlCount: A probabilistic fusion algorithm for accurately estimating occupancy from 3D camera counts. Proceedings of the 3rd ACM International Conference on Systems for Energy-Efficient Built Environments, Palo Alto, CA, USA, 2016, pp. 147-156.
42. E. Hale, L.Lisell, D. Goldwasser, D. Macumber, J. Dean, I. Metzger, A. Parker, N. Long, B. Ball, M. Schott, E. Weaver, L. Brackney, Cloud-Based Model Calibration Using OpenStudio, eSim 2014, Ottawa, Canada, May 7-10, 2014.
43. Functional Mock-up Interface (FMI) Standard. Available from: http://fmi-standard.org/
44. EnergyPlusToFMU, Simulation Research Group - Lawrence Berkeley National Laboratory. Available from: https://simulationresearch.lbl.gov/projects/energyplustofmu
45. EPQuery. Available from: https://github.com/sdu-cfei/epquery
46. Weather Data for Simulation. Available from: https://energyplus.net/weather/simulation
47. J. Li, A software approach for combining real time data measurement and building energy model to improve energy efficiency, Technical Report No. UCB/EECS-2014-37, EECS Department, University of California, Berkeley, May 1, 2014.
48. G.P. Henze, M. Krarti, Predictive Optimal Control of Active and Passive Building Thermal Storage Inventory, Final Report, October 2005. Available from: https://www.osti.gov/scitech/servlets/purl/894509-GH9Mqf/
49. P. May-Ostendorp, G.P. Henze, C.D. Corbin, B. Rajagopalan, C. Felsmann, Model-predictive control of mixed-mode buildings with rule extraction, Building and Environment 46 (2011) 428-437.
50. S. Prívara, J. Cigler, Z. Vána, F. Oldewurtel, C. Sagerschnig, E. Zácecková, Building modeling as a crucial part for building predictive control, Energy and Buildings 56 (2013) 8-22.
51. COORDICY Project. http://www.sdu.dk/en/om_sdu/institutter_centre/centreforenergyinformatics/research+projects/coordicy

List of Tables

Table 1. Causes of energy performance gaps in buildings

Design Phase	Construction Phase	Operation Phase
- building energy modeling limitations and uncertainties - oversimplified inputs regarding the built quality and fabric performance - design complexity - performance targets miscommunication - unrealistic early design decisions - lack of integrated design principles considering energy consumption and indoor thermal comfort and air quality - failure to predict functional and stochastic changes - components and systems over-sizing and under-sizing - lack of energy modeling and simulation knowledge and skills - uncertainties and generic assumptions in weather conditions, occupancy patterns and behavior, heat gains and plug loads	- mismatch between the quality at the building handover and the quality at the design stage - changing requests from clients - poor commissioning - improper envelope assembly - economically-driven decisions affecting materials and systems selection leading to design modifications - improper components and systems integration	- lack of continuous commissioning - mismatch between design idealized assumptions and actual patterns - faulty systems and components - poor practice - lack of maintenance and service - occupants behavior and activities - lack of occupancy monitoring - variation in systems operation modes and changes in the use of the building - inappropriate building management and control strategies - faulty sensors and meters - lack of customers and residents knowledge in terms of energy efficiency and building operation

Table 2. Gap between monthly simulated and measured energy consumption data

	Heating (MWh)			Ventilation Electricity (kWh)			Lighting Electricity (kWh)		
	Actual	Simulation	Deviation (%)	Actual	Simulation	Deviation (%)	Actual	Simulation	Deviation (%)
Sep	2.43	2.56	5.3	4470.9	4650.3	4.0	4840.9	5024.8	3.7
Oct	25.24	23.12	-8.4	3212.2	3268.5	1.8	6094.9	5894.4	-3.3
Nov	44.50	45.94	3.2	4224.1	3932.1	-6.9	5872.7	6106.1	3.9
Dec	46.51	48.16	3.6	3257.9	3193.3	-1.9	5800.5	5966.2	2.7

Table 3. OU44 building overall energy consumption – Simulation vs Actual data

	Actual	Simulation	Dynamic Performance Gap (%)
Heating (MWh)	70.81	72.82	-2.85
Overall Electricity (MWh)	23.87	24.70	-3.47
Lighting Electricity (kWh)	5972.46	6047.24	-1.25
Ventilation Unit 1 Electricity (kWh)	1212.63	1240.78	-2.32
Ventilation Unit 2 Electricity (kWh)	1165.43	1104.68	5.21
Ventilation Unit 3 Electricity (kWh)	1151.29	1166.10	-1.28
Ventilation Unit 4 Electricity (kWh)	1332.23	1280.61	3.87

Figure Captions

Fig. 1: OU44 Building

Fig. 2: Monthly measured consumption for lighting, ventilation and heating in 2016 compared to BE10 predictions

Fig. 3: Overall online performance monitoring and evaluation methodology

Fig. 4: OU44 building sketchup 3D model

Fig. 5: Screenshot of the OU44 building OpenStudio model

Fig. 6(a-b): (a) 3D stereovision camera unit and (b) a sample video capture from camera unit

Fig. 7(a-b): (a) Erroneous sensor counts and (b) corrected counts using PLCount

Fig. 8: Site measured outdoor air drybulb temperature, wind speed and direct solar radiation from Sep to Dec 2016 used for model calibration

Fig. 9(a-c): Comparison between BE10 numbers, Energyplus model simulations and measured data for (a) heating; (b) ventilation electricity and (c) lighting consumption

Fig. 10: Dashboard platform developed as a part of the ObepME tool

Fig. 11: Simulated and measured daily heating consumption reported by ObepME tool

Fig. 12: Simulated and measured daily lighting consumption reported by ObepME tool

Fig. 13: Simulated and measured daily ventilation electricity consumption reported by ObepME tool

Fig. 14(a-b): Dynamic energy performance gap for (a) heating, total electricity, lighting electricity and (b) ventilation electricity consumption

Figure 1: OU44 Building

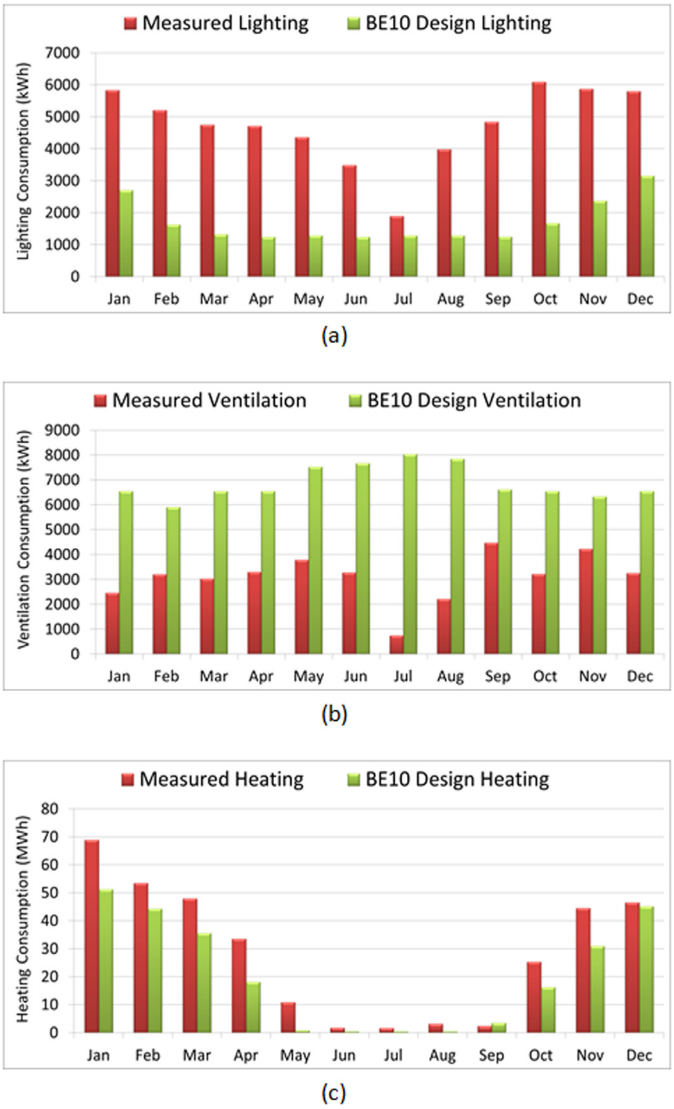

Figure 2: Monthly measured consumption for lighting, ventilation and heating in 2016 compared to BE10 predictions

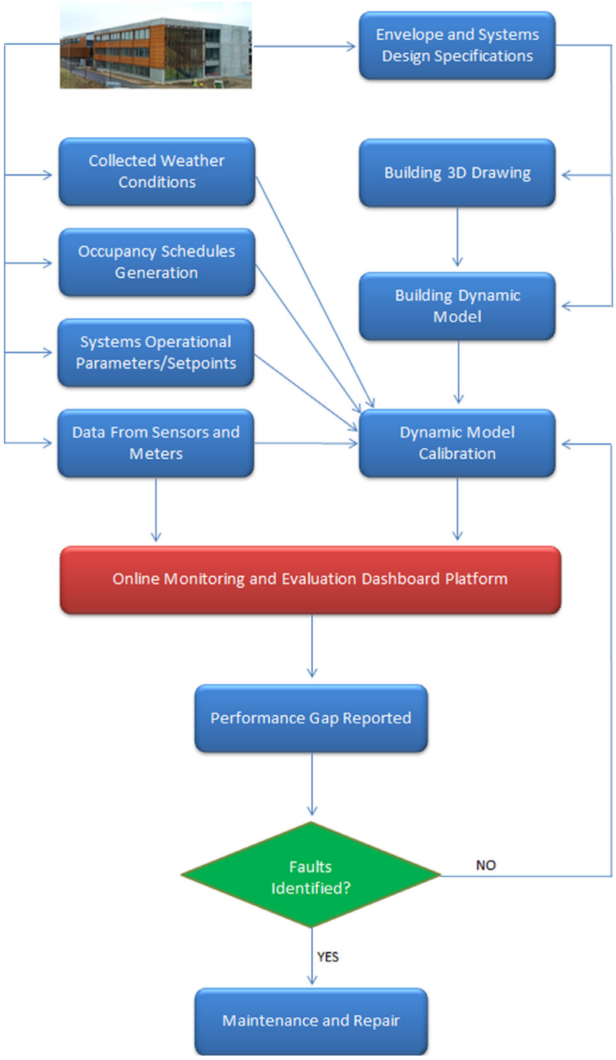

Figure 3: Overall online performance monitoring and evaluation methodology

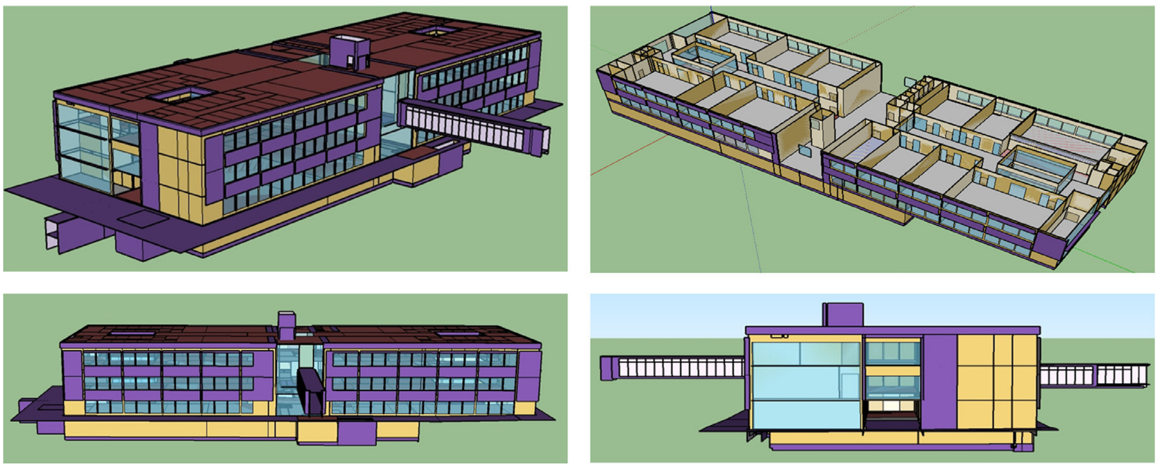

Figure 4: OU44 building sketchup 3D model

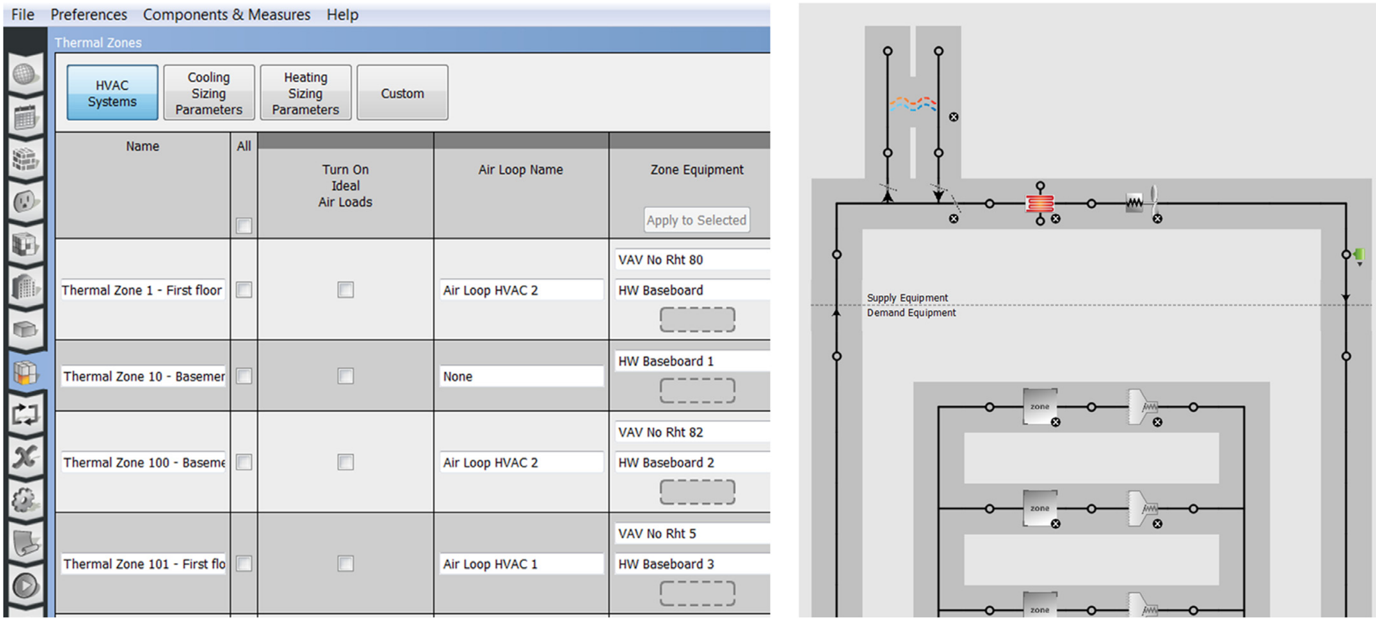

Figure 5: Screenshot of the OU44 building OpenStudio model

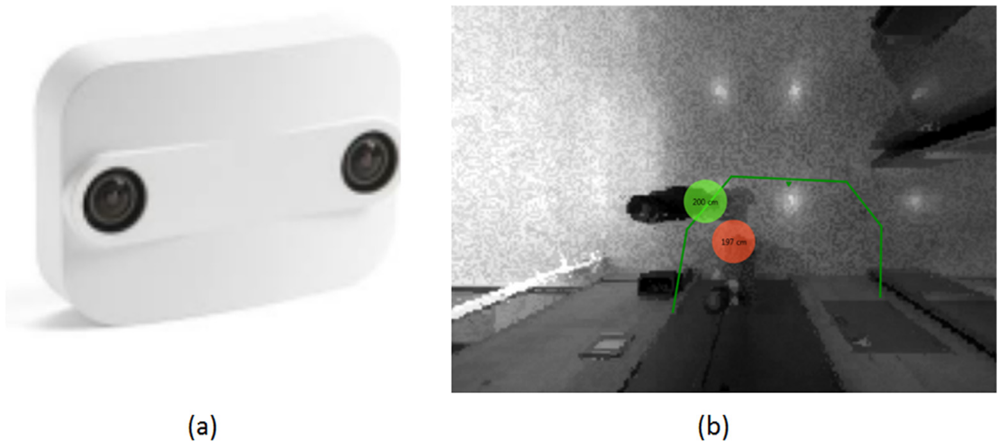

Figure 6: (a) 3D stereovision camera unit and (b) a sample video capture from camera unit

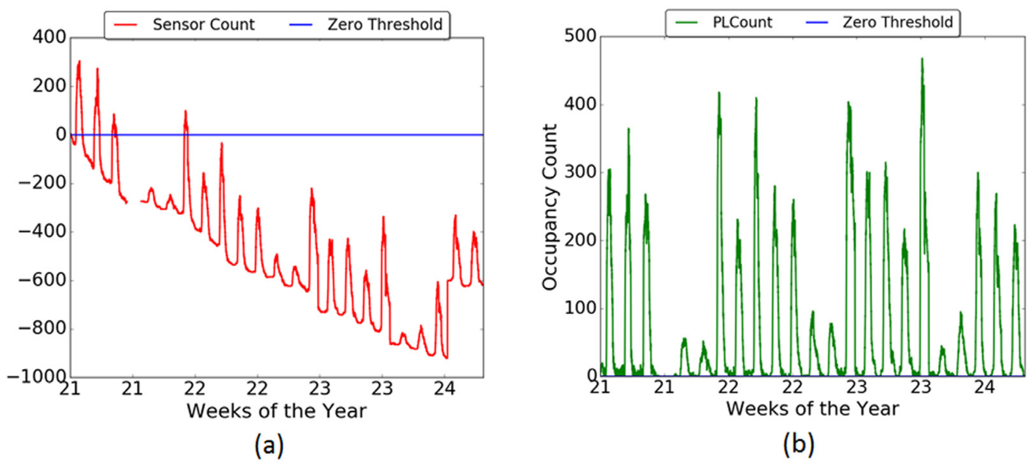

Figure 7: b): (a) Erroneous sensor counts and (b) corrected counts using PLCount

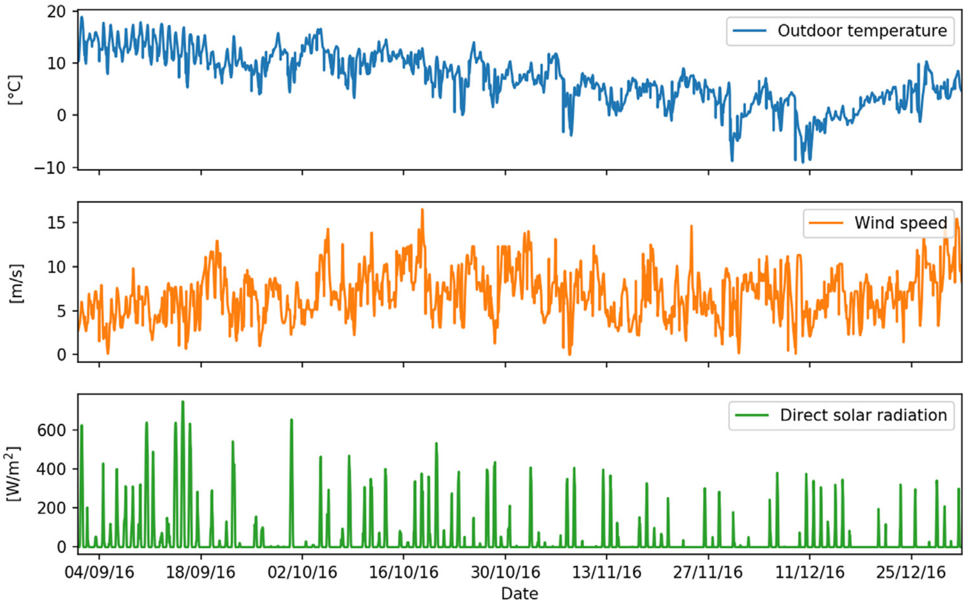

Figure 8: Site measured outdoor air drybulb temperature, wind speed and direct solar radiation from Sep to Dec 2016 used for model calibration

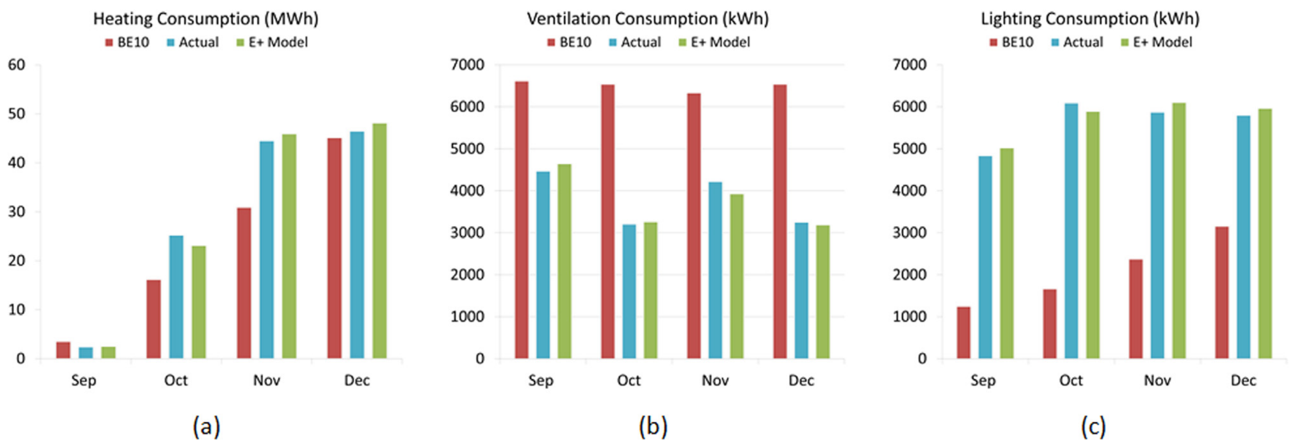

Figure 9: Comparison between BE10 numbers, Energyplus model simulations and measured data for (a) heating; (b) ventilation electricity and (c) lighting consumption

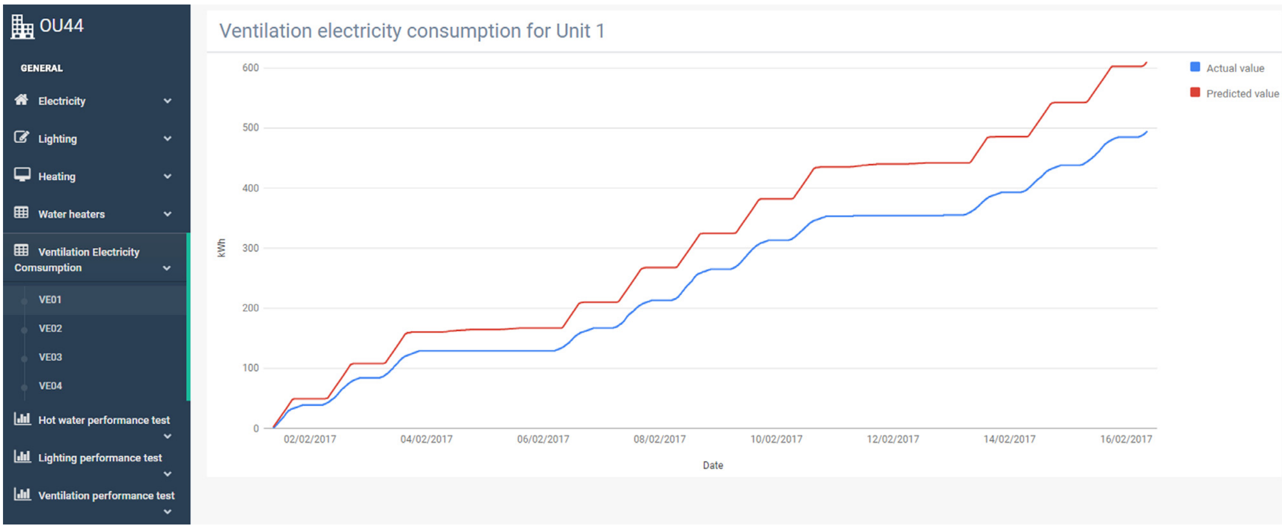

Figure 10: Dashboard platform developed as a part of the ObepME tool

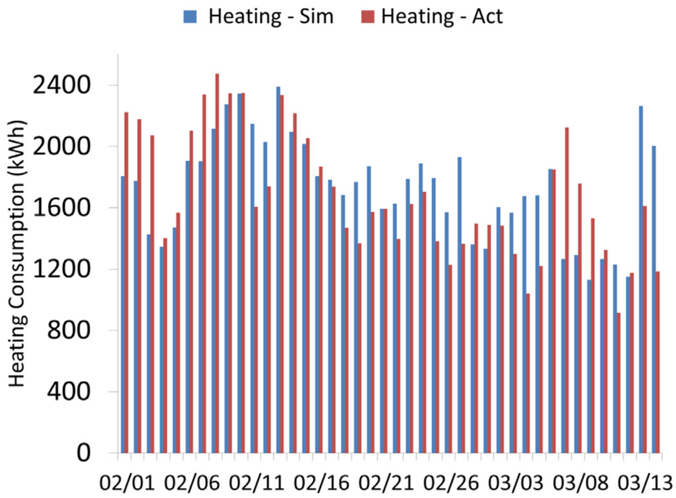

Figure 11: Simulated and measured daily heating consumption reported by ObepME tool

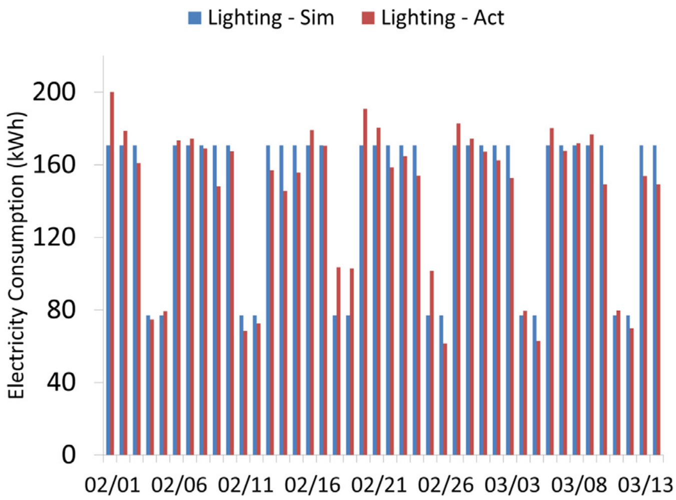

Figure 12: Simulated and measured daily lighting consumption reported by ObepME tool

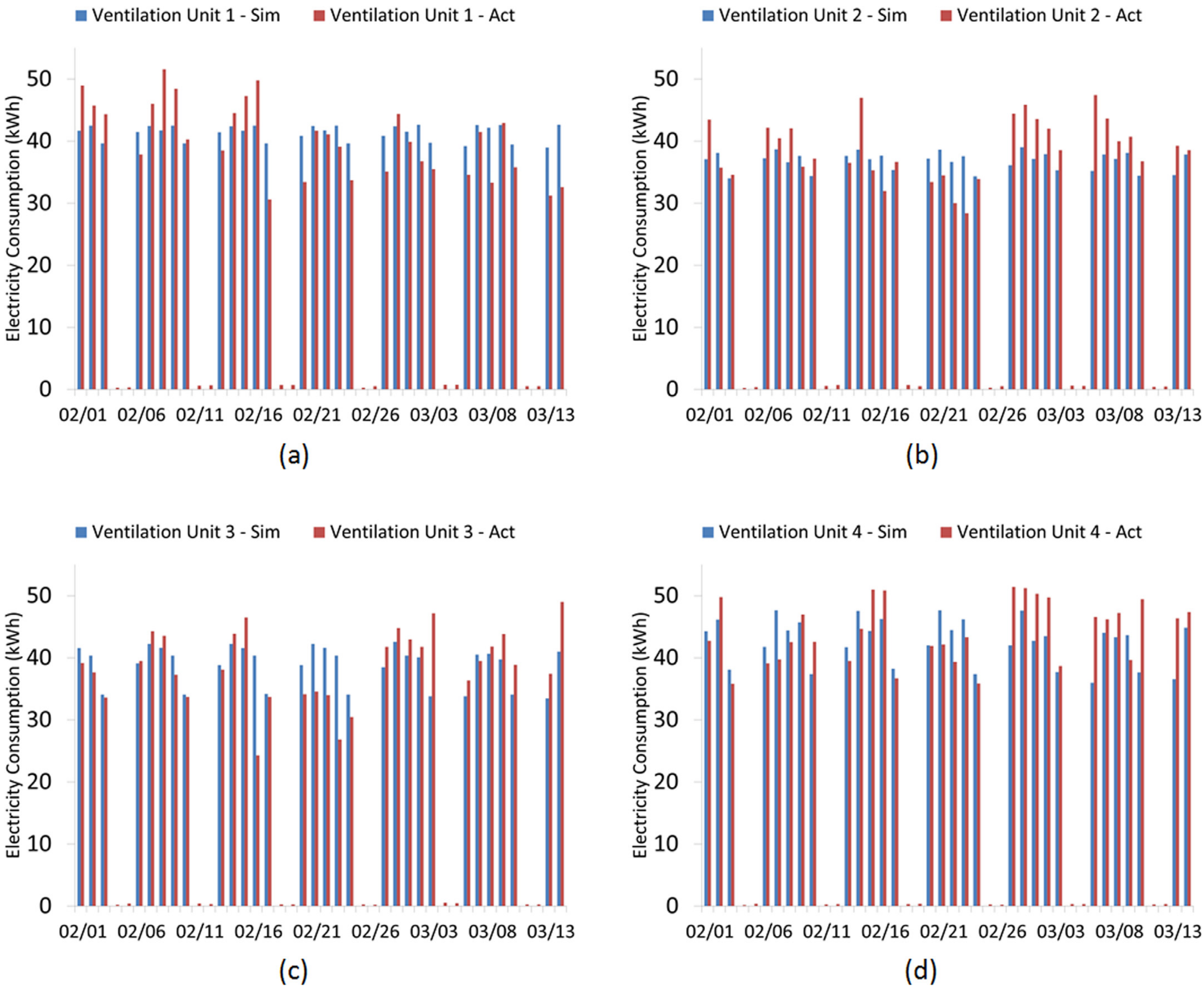

Figure 13: Simulated and measured daily ventilation electricity consumption reported by ObepME tool

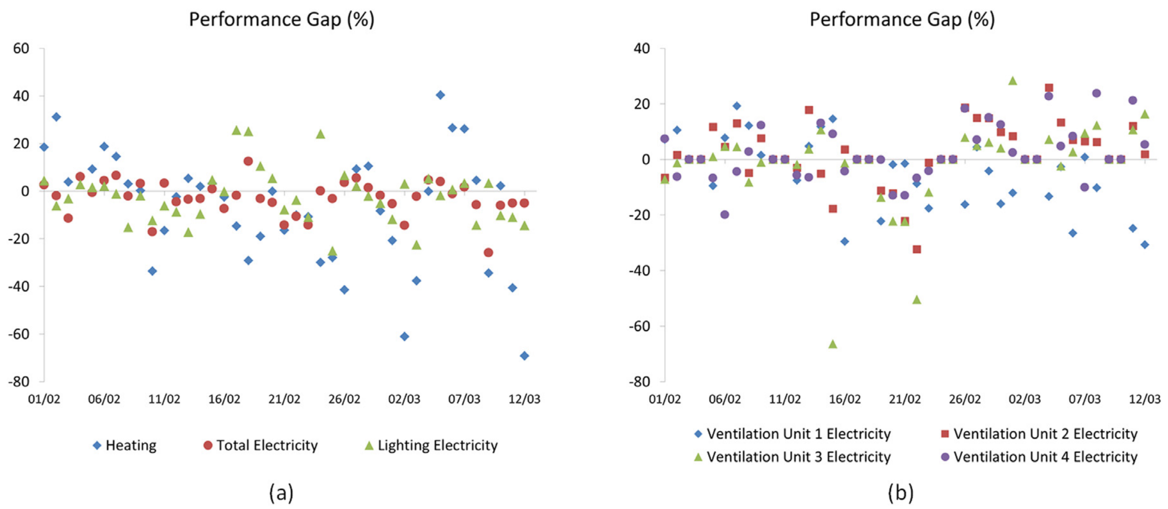

Figure 14: b): Dynamic energy performance gap for (a) heating, total electricity, lighting electricity and (b) ventilation electricity consumption