Online Energy Performance Monitoring and Evaluation for Continuous Commissioning in a Danish Office Building

Muhyiddine Jradi[1*], Na Liu[1]

[1] Center for Energy Informatics, University of Southern Denmark, Odense, Denmark
* *corresponding author: mjr@mmmi.sdu.dk*

Abstract

The development, implementation, and evaluation of an online building energy performance monitoring and evaluation 'ObepME' platform in a 2600 m^2 Danish office building is presented and discussed. A whole building dynamic energy model was developed in EnergyPlus and calibrated using actual onsite data. The calibrated model is then used as a basis for continuous and automated commissioning. A list of performance tests was developed targeting energy consumption on different levels. An online dashboard was created to automatically compare and visualize model simulations and actual building consumption as part of the building continuous commissioning. The model development and calibration along with ObepME implementation are presented in this paper. Major findings from the continuous commissioning platform and examples of malfunctions observed are reported and analysed.

Introduction

Relying on the fact that a building has met the energy requirements and adhered to the regulations at the design stage doesn't guarantee that it will live up to the expectations afterwards. In most cases, there is a clear mismatch between actual energy consumption and the predicted numbers, defined as the 'building performance gap' (Frei et al., 2017). A main reason behind experiencing such gaps, in both newly built and retrofitted buildings, is the lack of building continuous commissioning and the absence of any feedback to designers, consultants and owners after building construction and handover. In this context, a large block of studies and practical investigations have been presented in the recent decade aiming to uncover the various aspects related to energy performance gaps in buildings and providing methodologies to better characterize and reduce this gap, and thus eliminating losses and enhancing the overall performance.

In this regard, a recent study considered a pool of 62 buildings aiming to monitor the dynamic performance and evaluate the gap between the predicted numbers at the design stage and the actual reported consumption data (Van Dronkelaar et al., 2016). As a result, an average performance gap of 34% was reported between expected energy use numbers and real collected data from energy meters. A large comprehensive review of more than 200 theoretical and practical investigations in the field of energy performance gap was carried out (Zou et al.,

2018), highlighting that the causes of building energy performance gaps could be divided as 1) Design and simulation related causes, 2) Construction related causes and 3) Operation related causes. Based on the findings of the comprehensive review and assessment, major frameworks, and recommendations for reducing the performance gap in building and improve the performance were reported. One of the major suggested approaches is the implementation of continuous commissioning processes employing dynamic full scale building energy models. This will reduce the inaccuracies and uncertainties in the evaluation caused by the large assumptions at the modelling and simulation stage and will allow systematic monitoring and continuous performance testing over the whole life cycle.

Building Continuous Commissioning

Overall, the lack of operational performance testing and building continuous commissioning has been highlighted as a major reason for energy losses and performance gap in buildings. Continuous commissioning was defined by the IEA Annex 40 (Visier and Buswell, 2010) as being a "quality-oriented process for achieving, verifying and documenting whether the performance of a building's systems and assemblies meet defined objectives and criteria". While initial commissioning applications at the end of the construction stage and before the building handover have demonstrated substantial technical and economic benefits, extending this process into the operational stage will lead to even more positive impacts on various levels and will ensure a proper operating building throughout the whole life cycle. Thus, with the large set of data collected onsite, a continuous commissioning platform will not only serve as a basis for performance testing and continuous monitoring but will also form a core to test and implement feasible control and management strategies and enhance the building flexibility and intelligence quotient.

In recent years, a number of tools were developed and implemented for automated and semi-automated building continuous commissioning (HVAC-Cx, 2017; Building Advisor, 2020; CommONEnergy, 2013). However, most of these tools and applications rely mainly on static data, design parameters, fixed thresholds and baselines as well as historic data and trends to serve as a baseline to evaluate the performance.

Considering the technical, economic, and environmental added value of building continuous commissioning and

performance testing, and with the gap between tools and frameworks and the energy efficiency goals to be attained, there is an urgent need to develop and establish systematic and comprehensive platforms and tools. Such tools will serve as a basis for continuous and automated building performance monitoring and evaluation and extend the commissioning capabilities from the design stage into the operational phase. In addition, these tools and platforms will serve as a basis for building energy systems operational optimization along with establishing a systematic and effective fault detection and diagnostics process on various building levels. This will allow timely interventions along with capturing and rectifying problems and systems malfunctions, and thus reducing losses and inefficiencies. Demonstrating the added value of continuous commissioning processes in buildings, a practical investigation considering 26 non-residential buildings was presented, where continuous commissioning was set and implemented (Bynum et al., 2008). The findings of the work have highlighted that the continuous commissioning process implemented has led to substantial savings on the energy use of up to 35%, with a very satisfactory payback period of less than 3 years.

In this regard, 'ObepME', a framework for building online energy performance monitoring and performance testing (Jradi et al., 2018), was developed to serve as a backbone for an automated and continuous commissioning process. The framework has two key pillars: energy simulations from a whole building dynamic performance model and actual data collected onsite from various meters. Under the developed framework, a set of building performance tests are performed, targeting various subsystems including HVAC components and units. The framework implementation, demonstration, and evaluation in a 2600 m^2 Danish office building is presented and discussed in this paper, along with building energy performance analysis and evaluation. A whole building dynamic energy model was developed in EnergyPlus and calibrated using actual data collected in addition to data from a weather station on the building roof. The calibrated model is used as a basis for continuous and automated commissioning, through simulating the expected building performance for the previous day and comparing the numbers with actual meter data. A list of performance tests was developed targeting energy consumption on different levels. An online dashboard platform was created to automatically compare and visualize model simulations and actual building consumption as part of the building continuous commissioning. The commissioning findings and results are analysed and discussed. As part of the commissioning platform implementation in the considered building, two cases of malfunctioning systems were captured and reported by the platform and are highlighted in this paper to demonstrate the technical added value of the continuous building performance evaluation tool. The work is carried out under the 'Automated Auditing and Continuous Commissioning of

Next Generation Building Management Systems' (BuildCOM) research project (Jradi et al., 2021), aiming to develop and demonstrate innovative tools for automated building management system auditing and continuous building commissioning, providing a basis for a methodical auditing and evaluation process for the design of next generation building management systems.

ObepME Tool

ObepME, a tool for online building energy performance monitoring and evaluation will be employed as a basis for the continuous commissioning platform in this work. ObepME is a holistic dynamic energy model-driven application with a set of built-in building performance tests on various levels of the building. The overall tool operation framework is shown in Figure 1, where the performance tests are constructed and executed employing two core inputs:

1- Holistic building dynamic energy performance model simulations on different levels
2- Energy meters data collected on various components and sub-components in the building

In the implementation of the continuous commissioning platform, the first step is the design and development of the overall building energy performance model. Such model will comprise all building specifications and characteristics, including physical envelope information, energy systems layout and various building services. Then, data from the metering infrastructure in the building is set to be collected, including whole building energy meters in addition to sub-level meters on energy systems and components performance. Moreover, external data inputs are considered for the performance simulation to be executed, including weather conditions data, building occupancy counts and schedules along with operational setpoint data from various building systems management and control units. As energy simulations are completed using the dynamic building model, predictions are compared to actual onsite data from the corresponding meters and streams. The comparison will then automatically and continuously characterize and evaluate the performance gap in the building at various levels.

ObepME setup in the building will serve as a core component in the process of fault detection and preventive maintenance. A performance gap identified progressively in the building will provide alarms on an anomaly, which could be in some cases a malfunctioning system, a broken component, or a controller fault. On a daily basis, ObepME will call for the simulation inputs listed above including internal and external inputs, and performance simulation of the building performance for the previous day is carried out and reported. Parallel to the model simulations, corresponding real data are also fetched in the platform and compared to the predicted numbers in an automated and continuous manner. The whole continuous commissioning platform operation is executed using an online building energy performance

simulator reported in an earlier study by the authors (Jradi et al., 2018), where the building EnergyPlus model is exported to a Functional Mock-Up Unit (FMU) file, which is executed and run then employing a Functional Mock-Up Interface (FMI)-compatible framework with the aid of the EnergyPlusToFMU application. At the end of the simulation, the model outputs are mapped to the corresponding streams in the central database, which in a parallel manner store the actual data collected.
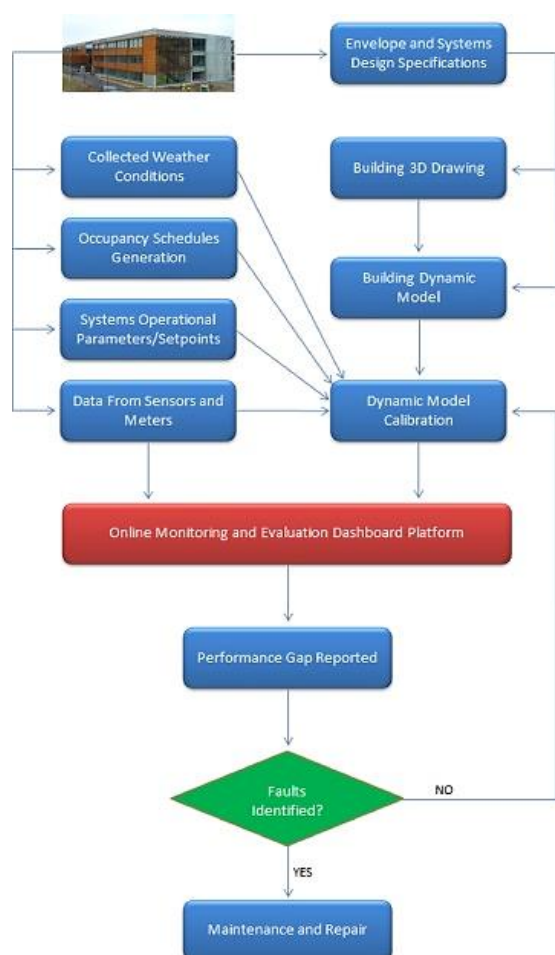

Figure 2: Dashboard components and data interactions.

The dashboard receives and visualizes two different types of streams, energy simulation streams and actual onsite building data streams. Onsite data from different meters and submeters are read and stored in a data repository employing an EnergyKey driver, where sensor data are pushed in by KNX drivers. In addition, using an automation service in Java, the online energy simulator is set and scheduled to run daily. Performance predictions are then pushed to a central database repository, the same repository in which the actual meter data are collected. Thus, the online dashboard application interacts with the actual data and simulation streams from the centralized data repository. First, data is queried with an SQL-like syntax. Using this data, the dashboard algorithm evaluates the performance gap for each streams' combination. The resulted gaps in percentage are then displayed via a friendly user interface, in the form of gauge charts produced and personalized by elements form the dash core components library. The readings of the gauges are thus updated on a daily basis, following the timestep of the simulation outputs of the online simulator.

Case Study

A case study of a Danish university office building is considered for investigation to implement and assess the continuous commissioning platform developed, aiming to monitor and evaluate the overall building performance. The 2600 m^2 building, shown in Figure 3, was built in 1995, comprising two floors and a small basement for HVAC installations. It is majorly used as an office building by staff and researchers on a daily basis. The building comprises 110 zones, with the majority being personnel offices, in addition to meeting rooms, research group rooms, laboratories and seminar rooms. A summary of the building physical envelope and constructions along with the energy supply systems is provided in Table 1.

Figure 1: ObepME tool operational framework.

Building Performance Dashboard

To better track the overall building performance and to visualise the continuous commissioning process and the performance gap evaluation on different levels in the building, an online performance monitoring dashboard was developed and integrated with the continuous commissioning and performance testing framework. The dashboard is developed using the Dash python framework for interactive building web applications. Automatically and continuously, the dashboard monitors and visualizes the building performance and the energy systems operation on different levels. The dashboard is generic in its development, but the interface is tailored to the specific building under investigation. The developed performance monitoring dashboard application with the major components and data interactions are shown in Figure 2.
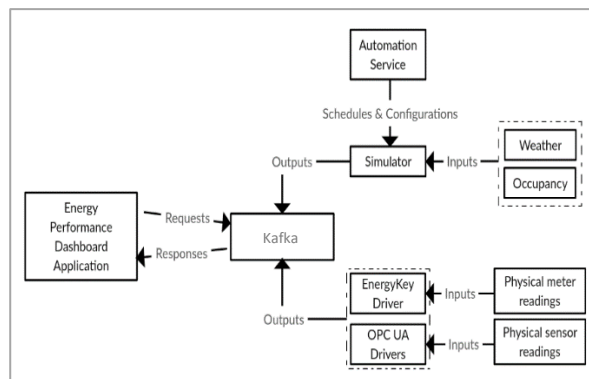

Figure 3: Office building case study.

Table 1: Case study building specifications.

Location	SDU Odense Campus
Indoor Heated Area	2600 m^2
Rooms	110 rooms
Window to wall ratio	0.26
Roof	300 mm concrete with insulation and bitumen
Exterior Walls	300 mm mainly concrete and insulation
Windows	Double-glazed windows
Heating System	In-direct district heating system with a heat exchanger on the main supply
Hot Water	Central production in an insulated storage tank
Space Heating	Radiators in every room with thermostatic valves
Ventilation System	Mainly natural ventilation with individual mechanical ventilation units in laboratories and specific rooms
Lighting	A mix of 100W halogen lights and fluorescent lights in the offices
Equipment	Mainly laptops, screens, printers, kitchen equipment.

To satisfy the space heating and domestic hot water needs, an in-direct district heating system is employed, with two heating sub-stations located in the building basement along with a heat exchanger on the main supply. Hot water is produced in an insulated storage tank in the building basement. For space heating, radiators are employed in every room and are equipped with thermostatic valves for water supply control. In terms of ventilation, the building majorly relies on natural ventilation using controlled operable windows. However, a main mechanical ventilation system is also integrated to satisfy the indoor air quality and thermal conditions in specific rooms, in particular the laboratories and kitchens. On the other hand, no cooling system is implemented. For lighting, a mix of 100 W halogen lights in the corridors, and LED tubes in the offices are used. As most of the building space is for office use, the building equipment is mainly laptops, computers, printers, screens, in addition to lab devices and kitchen equipment. The building thermal envelope complies with the BR95 Danish building regulation, and the external walls are made of heavy thick layers of concrete with additional insulation. Considering the Danish energy rating classes of buildings, the building is currently labelled as class 'D'.

In terms of the building metering and sensing infrastructure, the building is equipped with electricity and heating meters on the whole building level, but also on the level of each of the energy supply components, including domestic hot water, space heating, ventilation, and lighting. In addition, each room is equipped with PIR and illuminance sensors which are used to control the lighting system operation. For operation control and management, the building has a Schneider Electric structureware building automation system, managing various systems and services. In addition, the building has two occupancy counters on each of the building entrances to track the number of people. The building has also an onsite weather station set up on the roof allowing instant recording of climatic conditions including ambient temperature, wind speed and solar irradiation. The Kafka platform is used as an interface to store data collected from the building metering and sensing infrastructure on various levels and is exposed through a central platform. The use of Kafka aids data acquisition, collection, labelling and pre-processing. It also provides capabilities for post-processing of data collected from various meters and sensors, and thus facilitates the use of such data in different applications including performance monitoring, operational control and management and benchmarking.

Building Energy Modelling

Holistic Energy Model Development

A holistic dynamic energy performance model was developed for the considered case study building, taking into consideration various information on the building design specifications, envelope characteristics, energy systems, building services, loads, and operational parameters. In the development of the full-scale energy model, the white-box holistic whole-building energy modelling and performance simulation framework set by Jradi et al., (2017) was used and implemented for the considered case study. The framework employs a set of tools, including Sketchup Pro for 3D architectural model design and development, OpenStudio as a user-friendly interface for building specifications and energy model definition and EnergyPlus as a well-validated energy simulation engine.
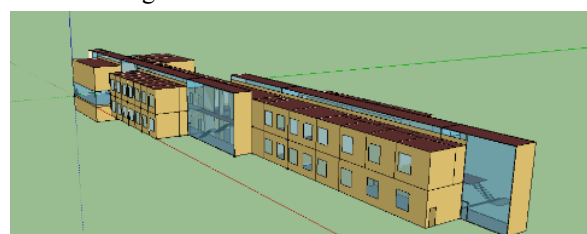

Figure 4: 3D model of the case study building.

Thus, the first step was to develop the 3D architectural model in Sketchup, as shown in Figure 4, taking into consideration all information on the building geometry, orientation, floors, and spaces allocations. This has resulted in a building model with 110 thermal zones. The 3D model was then imported in OpenStudio where all the energy model inputs are introduced, including envelope properties, energy systems layout, services, loads, and schedules. Finally, EnergyPlus simulation engine was used to run a full-scale dynamic energy simulation to predict the overall performance of the building at different levels.

Energy Model Calibration

As the whole full-scale energy model of the building is developed, it is time to calibrate the model to ensure that it provides a good characterization of the building performance and is capable to provide satisfactory results

and predictions with an acceptable accuracy. Such calibrated dynamic energy model is key to serve as a basis for the systematic continuous commissioning platform and to provide effective performance monitoring and evaluation services. The calibration for the considered case study building is carried out considering actual data collected onsite from various meters and submeters for an operational period of 5 months from January to May. The period is chosen as it characterizes a standard building use pattern post-COVID pandemic where staff and students are back to the building physically carrying out work and study activities again as normal. In addition to the data collected from meters onsite, actual weather data collected by the weather station, including ambient air temperature, wind speed and solar irradiation, was used as input to the energy model simulation engine to aid the calibration process. In addition, detailed occupancy schedules and loads allocations in the building were introduced as part of the energy model based on a full-scale survey of the various spaces and rooms. Such loads and schedules were used to overwrite the standard default and generic schedules in the model. Moreover, system operational parameters including setpoints, automation control thresholds and management patterns are included to a large extent as part of the energy model developed.

In carrying out the model calibration, the proposed dynamic energy modeling calibration framework in OpenStudio by Hale et al. (2014) was used. However, the framework was upgraded and instead of considering the total heating and electricity consumption numbers only, additional submeters were used in the calibration including the domestic hot water consumption and the ventilation system preheating consumption. Taking into account the framework highlighted above by Hale et al., the parameters considered in this study include space infiltration rates, pump head, lighting and equipment schedules, devices efficiencies, system setpoints, ventilation fans pressure rise and occupancy activity.

The Parametric Analysis Tool (PAT) in OpenStudio is used to aid the model calibration process by evaluating various parameters' combination scenarios and allowing simulating large number of scenarios simultaneously. Considering that the building was built in the 1990's, the Danish building regulation BR95 was used to set bounds for some of the parameters used in the calibration including infiltration rates, loads and efficiency of devices and services. Based on the large set of scenarios simulated, the scenario with the lowest deviation considering the individual daily energy consumption performance indicators was chosen to be used as a basis for the model which will be then used for the continuous building commissioning and performance testing.

Figure 5 (a to d) shows the overall results of the calibration process by comparing the daily predicted energy consumption with the actual reported energy consumption onsite for the (a) total heating, (b) total electricity, (c) domestic hot water and (d) ventilation
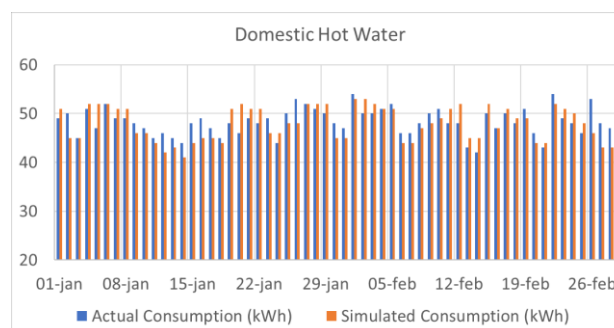
preheating. As highlighted in the figure, it is clear that the calibrated building model predicts the overall energy consumption at various levels in the building with acceptable accuracy. To evaluate the reported prediction uncertainty, the Root Mean Square Error is evaluated.
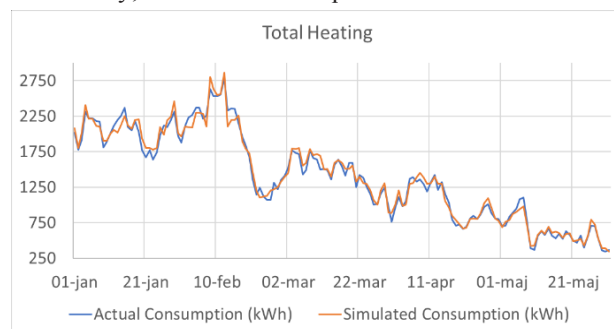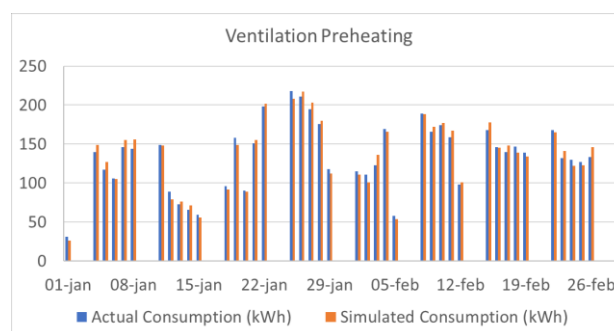

(a)
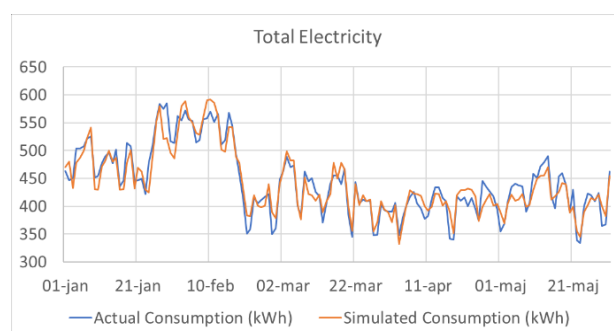
(b)

(c)

(d)

Figure 5: Energy model calibration results for (a) total heating, (b) total electricity, (c) domestic hot water and (d) for ventilation preheating.

Table 2 summarizes the average monthly RMSE for each of the four considered energy performance meters. Regarding total heating consumption, the maximum reported average RMSE is around 107 kWh in February, where the maximum daily uncertainty between the simulated and the actual numbers reported is 17.4%. For total electricity, the maximum RMSE is reported in January with 24 kWh, and a corresponding maximum uncertainty of 14.7%. On the other hand, the RMSE for DHW ranges from 1.4 kWh in May to 3.1 kWh in March, with a maximum daily uncertainty in the predictions of around 13.8%. Finally, the maximum RMSE reported in the case of the ventilation preheating meter is around 7 kWh in March, with a maximum daily uncertainty of 16.3% between the simulated and actual consumption.

Table 2: Model calibration RMSE.

	RMSE (kWh)				
	Jan	Feb	Mar	Apr	May
Total Heat	95.71	107.56	73.09	59.91	50.26
Total Elec	23.97	20.03	13.88	18.91	18.41
DHW	2.85	2.59	3.09	1.75	1.48
Vent Heat	5.55	6.04	7.13	5.75	4.63

ObepME Continuous Commissioning Platform Implementation

The developed and calibrated building dynamic energy model was used and implemented as a basis to simulate the daily building energy performance automatically and continuously within the ObepME tool. In this section, the implementation of ObepME as a basis for an automated continuous commissioning platform in the case study building is presented. As described earlier, ObepME makes use of two major components to evaluate and report the energy performance gap at various levels, i) actual meter data collected on various levels in the building and ii) corresponding dynamic energy model simulations of the predicted energy consumption. The model simulations will then serve as a baseline and expected reference for a proper operation of systems and components. Results from the model simulations are automatically fed into the ObepME platform and the performance gap is thus calculated automatically at various levels. In this work, the performance gap is reported at four major levels, corresponding to the energy meters reported in the previous section. This includes (a) Total Heating, (b) Total Electricity, (c) Domestic Hot Water, and (d) Ventilation Preheating.

Monitoring the building performance on the level of each of the energy systems, and not only on the whole building level, will allow a more detailed assessment of the building performance, and provides higher capabilities and potential in capturing issues and faults at systems and components level. Additional systems in the building are also monitored, including the lighting system and building serves, but we have chosen 4 major energy meters to present in this paper. On a daily basis, the energy model within ObepME online simulator will read updated weather data including ambient temperature, wind speed and solar irradiation in addition to operational setpoint parameters and will then execute a daily energy performance simulation and report consumption at various levels. These predictions are then used in ObepME. with the help of the developed online dashboard, and compared to actual data collected from meters in the building for the same period. Along with performance gap evaluation, the dashboard then will automatically and continuously visualize the gap on a daily basis allowing performance assessment.

Energy Performance Monitoring Dashboard

*Figure 6: Performance Dashboard on Oct 25.*

In this regard, Figure 6 shows the performance testing results reported by the dashboard platform on October 25, with the four respective gauges of performance gap. It should be noted that the dashboard application is developed as a means of performance visualization in the building for 'normal' building users, while the cumulative historical daily performance gap calculated on different levels are also reported in a performance monitoring centralized database platform for a more technical assessment by experts and technical services staff. As shown in the figure, the respective performance gap reported on October 25 is -4.9 %, -16.3 %, 25.8 % and 11.7 % for the total heating, total electricity, domestic hot water, and ventilation preheating. Overall, the numbers demonstrate an acceptable performance of the building in the considered day with no major gaps.

While the online performance gap dashboard will provide a visualization on the daily reported performance gap on various levels in the building, Figure 7 (a-b) provide a more detailed technical assessment of the building performance by reporting the daily performance gap over a period of two months, October and November. The figure highlights the daily performance gap percentage reported for (a) the total heating consumption and (b) the total electricity consumption. Looking at the figures, it is shown that the maximum daily performance gap reported in this period was around 20% for total heating consumption and around -16% for the total electricity consumption. In addition to that, the RMSE reported in

this period was around 70.1 kWh for heating consumption and 25.7 kWh for electricity consumption.
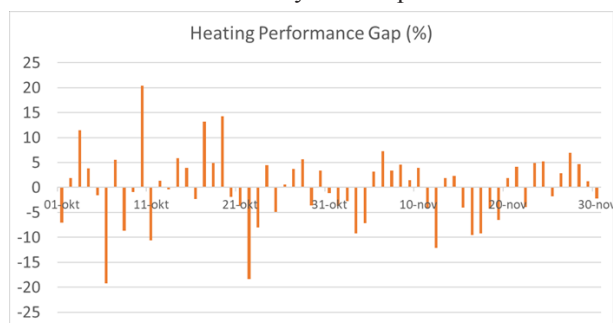
(a)
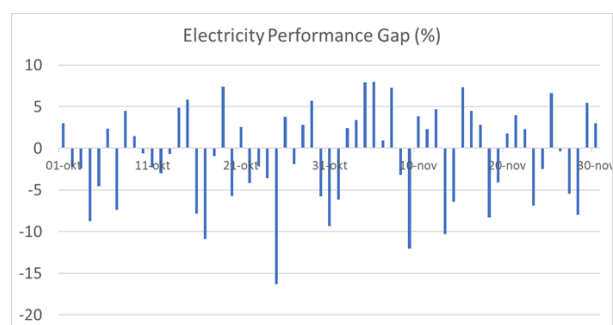
(b)

Figure 7: Daily performance gap reported for (a) total heating and (b) total electricity.

System Level Commissioning

While the numbers shown in Figure 7 could to some extent highlight and evaluate if the building is performing as expected most of the time, such assessment indicators as the total heating and electricity can't identify and locate if there is an error or fault on the level of the systems and components. A deep continuous commissioning process with detailed performance monitoring on the level of the systems is needed in such cases, including ventilation, lighting, equipment, and services consumption breakdown. In this section, we will present a couple of cases where errors and faults at the level of the building systems are identified by tracking and monitoring the performance of the individual component in question.

Domestic Hot Water System

One of the major building systems which are commissioned, and its performance is being continuously monitored and evaluated is the domestic hot water system. The domestic hot water supply in the building is provided majorly by district heating with the help of an electric heater onsite. Thus, hot water is then accumulated in an insulated storage tank and delivered by hot water circulation pumps to the two building floors. Figure 8 reports the results attained as part of implementing ObepME to monitor the energy performance at the level of the DHW in the month of October. Overall, the figure shows that in the majority of the month the system is operating as expected with no major gaps, except for the period from 20 to 24 October, where the online

performance monitoring and evaluation dashboard highlighted an increase in the overall performance gap, exceeding 250% on October 22. This highlighted a very low energy consumption at the building level compared to the expected consumption. Considering this performance gap, an alarm has been generated and the technical services staff has been approached, where the issue was related to a controller malfunction at the level of the storage tank supply side. As the fault is eliminated, it is clear that the operation is back to normal limits after this period with an acceptable gap as highlighted in Figure 8. This case is a clear example that while excess consumption is not desirable, very low consumption could also be an indication of a problem or a fault.
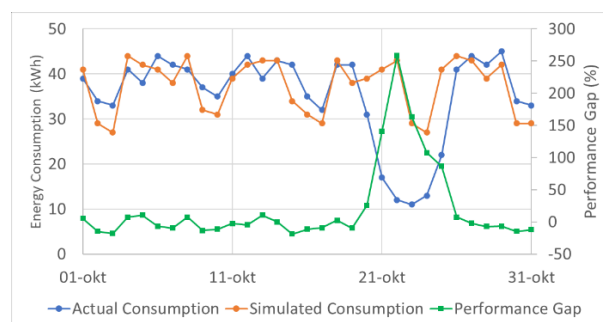

Figure 8: DHW Commissioning results.

Ventilation Preheating System

Another major building system which is also under the radar of the continuous commissioning platform and the overall performance monitoring and evaluating tool ObepME is the ventilation preheating system. The ventilation preheating in the building is provided by a heating loop supplied by the district heating station and connected at the supply side of the main mechanical ventilation system supplying the majority of the labs, meeting and group rooms. Figure 9 provides an overview on the results reported by ObepME for the month of November, showing both the actual energy consumption and the corresponding model predictions on a daily level. In addition, the figure shows the performance gap reported also on a daily basis.
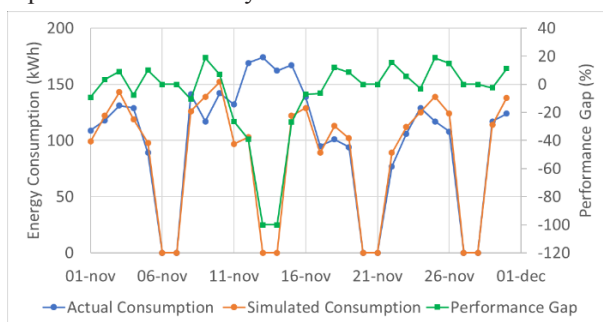

Figure 9: Ventilation preheating Commissioning results.

Again, in this case it is shown that the system has a satisfactory performance within the acceptable limits during the whole month, except for the period from 11 to 15 November, where the performance gap increases drastically, including a weekend where the system is

found to be operating and consuming excess energy compared to a standard operation day. This issue was also reported, and a fault was highlighted at the level of the system fan operation controller. After rectifying the issue, a normal operation was then restored as highlighted in the figure.

Conclusion

In this work, an online building energy performance monitoring and evaluation platform is developed and demonstrated to serve as a basis for an automated continuous commissioning of instrumented non-residential buildings. The proposed platform has two key pillars, dynamic energy model simulations and actual meter data collected onsite. Using these inputs, it evaluates energy performance gap at various building levels in an automated and continuous manner. The platform was tested and implemented in a Danish office building, including the energy model development and calibration, software components design and integration, data collection and storage, and the design of an online dashboard platform. In the paper, two cases of system malfunctioning are reported and discussed with the corresponding performance gap monitored and evaluated. The findings highlight the importance of system and component-level commissioning in buildings as an alternative to the standard high level performance monitoring. The use of the proposed dynamic energy model-based approach for performance monitoring and continuous commissioning brings a major added value in such applications due to the model capability in adopting and taking into account the dynamic changes in the building operation patterns as well as the external factors including the weather conditions. Moreover, it was highlighted in a recent technical study that the development of a holistic full-scale building dynamic model yields an overall payback period of around 1–2 months. This supports employing such models as a basis to aid decision-making in terms of design, operation, control, and commissioning. In addition, the continuous and automated platform employed allow timely intervention and thus saving costs and resources. The platform is currently running in the building as a basis for continuous commissioning, serving a systematic fault detection and preventive maintenance process.

Acknowledgement

References

Building advisor (2018). Available from: http://ecostruxurebuildingadvisor.com.

Bynum, J., Claridge, D.E., Turner, W.D., Deng, S., and G. Wei (2008). The cost-effectiveness of continuous commissioning over the past ten years. *Proceedings from the 8th International Conference for Enhanced Building Operations (ICEBO 2008)*. Berlin (Germany), 20-22 October 2008.

CommONEnergy (2013). Available from: http://www.commonenergyproject.eu/continuous_commissioning_tool.html.

Frei, B., Sagerschnig, C., and D. Gyalistras (2017). Performance gaps in Swiss buildings: an analysis of conflicting objectives and mitigation strategies. *Energy Procedia 122*, 421-426.

Hale, E., Lisell, L., Goldwasser, D., Macumber, D., Dean, J., Metzger, I., Parker, A., et al. (2014). Cloud-Based Model Calibration Using OpenStudio. *Proceedings from eSim 2014*. Ottawa (Canada), 7-10 May 2014.

HVAC-Cx (2017). Available from: https://www.nist.gov/services-resources/software/hvac-cx-building-hvac-systems-commissioning-tool.

Jradi, M., Arendt, K., Sangogboye, F.C., Mattera, C.G., Markoska, E., Kjærgaard, M.B., Veje, C., and B.N. Jørgensen (2018). ObepME: An Online Building Energy Performance Monitoring and Evaluation Tool to Reduce Energy Performance Gaps, *Energy and Buildings 166*, 196-209.

Jradi, M., Boel, N., Madsen, B.E., Jacobsen, J., Hooge, J.S., and L. Kildelund (2021). BuildCOM: automated auditing and continuous commissioning of next generation building management systems, *Energy Informatics 4(2)*.

Jradi, M., Veje, C., and B.N. Jørgensen (2017). Deep energy renovation of the Mærsk office building in Denmark using a holistic design approach, *Energy and Buildings 151*, 306-319.

Van Dronkelaar, C., Dowson, M., Burman, E., Spataru, C., and D. Mumovic (2016). A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings. *Frontiers in Mechanical Engineering 1*, 17.

Visier, J.C. and R.A. Buswell (2010). Commissioning Tools for Improved Building Energy Performance, *ECBCS Annex 40 Project Report*. AECOM Ltd.

Zou, P.X.W., Xu, X., Sanjayan, J., and J. Wang (2018). Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives. *Energy and Buildings 178*, 165-181.