Dynamic Energy Model-Based Automatic Building Performance Testing for Continuous Commissioning

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Abstract

Relying on the fact that a building has met its energy targets at the design stage doesn't guarantee that it is going to perform properly in the operational phase. Generally, there is a clear mismatch between the actual energy usage and the expected levels, referred to as the 'building performance gap'. This paper presents an innovative framework for building energy performance monitoring and evaluation using a set of performance tests targeting various building energy subsystems. The framework employs a calibrated whole-building energy model to provide a dynamic baseline for assessment. The presented framework serves as a backbone for an automatic and continuous building commissioning process, supporting systematic building fault detection and diagnostics. The framework implementation in a highly energy efficient case study building is presented and discussed. A specific case of a malfunctioning ventilation unit, that was captured and reported by the implemented framework, is presented. This highlights the technical and economic added value of the framework in reducing the building performance gap and restoring a proper operation.

Introduction

The building sector has been prioritized by the EU (EU Commission, 2010), with a clear statement that improving the newly built and existing buildings energy performance is a major step towards achieving future energy and environmental goals. However, relying on the fact that a building has met the energy requirements and specifications at the design stage doesn't guarantee that it is going to perform as expected in the operational phase (De Wilde, 2014). In the majority of cases, there is an obvious mismatch between the actual energy usage and the predicted levels, defined as 'building performance gap'(Frei, 2017). Dealing with the building performance gap and considering the causes at the different building phases, a number of studies has developed methodologies and frameworks aiming to better characterize this gap and improve the building performance monitoring and evaluation. In a recent study, Van Dronkelaar et al. (2016) have investigated 62 buildings and compared the measured energy use with the numbers reported at the design stage. The results reported a 34% deviation in average between the actual and expected numbers. One of the major factors leading to buildings performance gaps is the lack of continuous building commissioning and the absence of any feedback to designers, engineers and owners after both building construction and handover and during the operational phase. IEA Annex 40 (Visier and Buswell, 2010) has defined building commissioning 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". Building commissioning process at the end of the construction stage was found to provide substantial benefits in terms of having a smoother building start-up and enhanced occupants comfort. Nevertheless, continuous commissioning beyond this stage into the building operation phase helps ensuring a long-term energy efficient performance of the building. This will provide high capabilities to implement feasible control and management strategies to improve the energy supply systems operation and thus raises the flexibility quotient of the building (Markoska et al., 2016).

Considering this added value of continuous building commissioning, there is an urgent need for a set of tools to improve and facilitate the initial building commissioning process at the design and construction stages, in addition to implementing an automated continuous commissioning process that runs throughout the building operational phase. Such tools could aid in verifying if the energy performance indicators are met and could help in developing and implementing operational strategies to optimize the performance of different systems in the building and enhance the flexibility quotient. In addition, continuous building commissioning and energy performance monitoring is an indispensable requirement for a systematic and effective fault detection and diagnostics process for energy conversion and supply systems operation. In general, this will lead to both technical and economic benefits in terms of avoiding excess energy use and increased operational costs due to malfunctioning of components. A recent study by the National Renewable Energy Laboratory (Kim et al., 2018) has indicated that there are significant energy and economic savings potential in the small commercial building sector through energy performance monitoring and implementing automated fault detection and diagnosis processes. However, these opportunities are not fully exploited due to the limited availability of automatic and continuous cost-effective building commissioning and monitoring tools. In addition, the report highlights the importance and the added-value of dynamic energy model-based continuous building commissioning and

https://doi.org/10.26868/25222708.2019.210200

fault detection and diagnosis tools in improving the holistic energy performance of buildings. In 2017, the 20 top-priority faults in the US small-commercial buildings have resulted in around 52750 GWh energy losses in addition to substantial $7 billion in operational cost (Kim et al., 2018). Moreover, based on data collected from 26 non-residential building sites, it was reported that implementing a proper building continuous commissioning process has the potential to save up to 35% on the building energy consumption, with a payback period of less than 3 years (Bynum et al., 2008). In addition, it was highlighted that the development of a detailed building dynamic energy model has an overall payback period of around 1-2 months, considering the potential of using such models to aid decision-making in terms of design, operation, control and commissioning (HOK, 2016).

In the recent years, multiple tools have been developed and implemented for automated and semi-automated building continuous commissioning (Building Advisor, 2018; HVAC-Cx, 2017; CommONEnergy, 2013). However, these tools rely in the continuous commissioning process on static thresholds and baselines as well as historic data and trends. The current study presents an innovative framework for automatic and continuous building energy performance monitoring and evaluation using a set of performance tests targeting various building energy subsystems and employing a calibrated whole-building energy model to provide a dynamic baseline for assessment. Such approach has not been reported in the literature and implemented in a real case building before. The major contribution of the study is using holistic dynamic energy performance models as a basis for continuous commissioning and fault detection and diagnostics in buildings. This will lead to reducing energy performance gaps in the operational phase and ensuring a proper operation of different building subsystems. The presented framework has two pillars: simulations from whole-building dynamic energy performance model and actual data collected onsite from various meters. The framework development and implementation in a highly energy efficient case study building is presented and discussed in this paper, along with building energy performance analysis and evaluation. The paper will present first the case study building considered for the analysis. Then, an overview of the energy performance monitoring and evaluation framework design and implementation is provided, including the full-scale dynamic building model development, model calibration, implementation of the developed framework in a case study university building in Denmark and the establishment of an online dashboard platform for performance visualization. Finally, a specific case of a malfunctioning unit that was captured and reported by the implemented framework is presented.

Framework for Continuous Building Commissioning

To serve as a basis for building automated continuous commissioning, a model-based framework for building energy performance monitoring and evaluation is designed and developed in this study. Figure 1 provides an overview of the developed framework, which has a list of performance tests targeting whole-building performance and energy sub-systems operation. In overall, the performance tests have two major inputs:

- performance simulations provided by the developed calibrated dynamic building energy model
- electricity and heating consumption data provided by the metering infrastructure implemented in the building

The developed building energy performance monitoring and evaluation framework comprises the following steps:

- A dynamic full-scale energy performance model is developed considering different building specifications and characteristics in terms of physical envelope and energy supply systems.
- Data collected from various energy meters in the building, recorded weather data, occupancy counts, and energy systems operational parameters are used to calibrate the dynamic building model.
- Continuously, the calibrated dynamic energy model is used to predict the energy performance of the building.
- Performance tests are executed for the different energy systems in the building, comparing both simulations from the building model and actual data from the corresponding meters.
- Performance gaps are automatically and continuously calculated and reported.

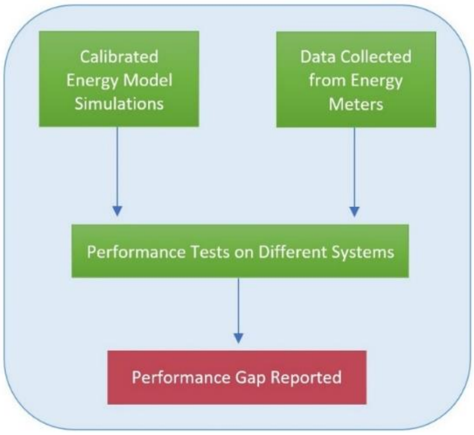

Figure 1: Continuous building commissioning framework overview.

Gaps identified based on the performance testing serve as a basis for the building fault detection and diagnostics. In case if no faults are identified, a re-calibration of the building energy performance model is then performed. In overall, the presented framework aims to establish an automated continuous commissioning process to ensure a proper operation of the different energy systems in the building, and as a result an energy efficient holistic building performance. The calibrated dynamic energy model is set to simulate the building performance on a daily basis, considering weather data, occupancy counts and operational parameters and setpoints implemented for the previous day. This is carried out using an online building energy performance simulator described earlier by the authors (Jradi et al., 2018), where the developed dynamic energy performance model in EnergyPlus is exported to a self-contained file of the Functional Mock-Up Unit (FMU), and run using a Functional Mock-Up Interface (FMI)-compatible framework using the EnergyPlusToFMU (2018) tool. As the simulation ends, the output variables are mapped to energy prediction streams in the centralized database platform, which also contains data streams collected from the building meters.

Case Study

An 8500m^2 building at the Odense Campus of the University of Southern Denmark, shown in Figure 2, is considered as a case study to assess the energy performance modeling, simulation, monitoring and evaluation framework. The OU44 building was built in 2015, with 3 floors and a basement for storage and technical installations. It is mainly used for teaching with classes running from 8 am to 6 pm, in addition to multiple study zones, personal offices, group and meeting rooms with an overall maximum capacity of around 900 people. The building was designed to comply with the Low Energy Class (Lavenergiklasse 15) of the Danish building regulation (Jradi et al., 2017). However, at the end of the construction stage, the initial commissioning of the building has reported a maximum primary energy use of around 41 kWh/m^2 of the heated indoor area. With that, the building complies with the strict future Danish building class 2020 in terms of buildings envelope and energy performance, to be one of the few in Denmark at that level. Regarding the energy conversion and supply scheme, the building space heating demand is covered by the local district heating loop, while two small electrical boilers are used to cover the domestic hot water needs. On the other hand, the building has no cooling system, being the standard in public buildings in Denmark. Thus, it relies on its ventilation system to attain a good indoor air quality and provide the additional cooling effect. The ventilation system comprises 4 balanced units, each with a supply and exhaust fan of a nominal capacity of around 17500 m^3/h. The ventilation units' operation is CO_2 driven, and they are connected to an air pre-heating loop in addition to an integrated rotary heat recovery wheel. Each of these 4 ventilation units serves approximately one quarter of the building area in a vertical perspective. The building is also equipped with an 80 m^2 system of photovoltaic panels with a power capacity of 12 kW, where the electricity generated onsite is used to run different services within the building.

Figure 2: OU44 university building.

Within the international research project COORDICY (2015), the OU44 building has been established as an energy living lab to carry out different research activities and projects. Such activities include investigating overall continuous building commissioning, energy supply systems and components, occupancy behaviour and patterns, data collection and validation, model-predictive control strategies, and demand-response events implementation. To aid this, the building has been equipped with a large number of energy meters and sensors on various levels, providing significant potential for detailed performance monitoring and effective operation control and management.

The metering infrastructure provides data on the overall electricity and heating consumption of the building, in addition to the energy usage of the 4 ventilation units, lighting consumption by zones and plug loads. In particular, 4 fully equipped test rooms have independent heating, electricity, lighting and equipment energy meters. The ventilation and heating systems in the building are equipped with multiple temperature and pressure sensors in addition to flow meters. Each room in the building has a set of sensors including CO_2, temperature, humidity, illuminance and PIR motion sensors. On the energy systems components level, all the rooms in the building are equipped with radiator valve position sensors, ventilation damper opening sensors and blinds position sensors. Considering that occupants behaviour and occupancy patterns have a significant impact on the energy use in buildings, 17 3D stereo-vision cameras were installed at different building entrances, corridors and in specific test rooms, to provide an estimate of the occupancy counts. The building has also an onsite weather station on the roof allowing instant recording of ambient temperature, wind speed and solar irradiation. The metering and sensor infrastructure is interfaced through the Simple Measurement and Actuation Profile (sMAP) protocol (Dawson-Haggerty et al., 2010) exposed through a central platform. sMAP facilitates data collection, labelling and pre-processing. In addition, it simplifies the post-processing and utilization of data for different applications including data validation, model calibration and occupancy prediction. The building chosen as a case study is a living lab empowered by a large number of meters and sensors, however this is not necessarily the case of any other building. In this regard, it should be noted that the required metering infrastructure for the energy model development and calibration along with the continuous building commissioning framework implementation constitute of the overall electricity, total heating, ventilation electricity and lighting meters and sub-meters. Saying that, additional indoor comfort sensors and floor and room level meters along with occupancy cameras would provide additional potential for detailed building performance monitoring and evaluation.

Performance Testing Dashboard Platform

A dashboard platform is developed to better report and visualize the performance tests results. The developed Dashboard is a Python application, built using 'Dash', a

Python framework for building web application (Dash, 2018). It monitors and evaluates building energy performance by reporting the performance tests results and comparing actual building performance with simulated building performance. The dashboard platform developed is specific to the building case study considered. Moreover, the current dashboard version monitors thermal comfort and indoor air quality and visualizes the average hourly temperature and CO_2 levels of the 27 large teaching rooms and study zones in the building. Figure 3 illustrates the data interactions within the dashboard application.

There are two types of data in connection with the application - actual data and simulated data. Actual data is generated by physical meters and sensors which are equipped inside the building. The generated meter data is then read and transmitted to the data repository smoothly through an EnergyKey driver and the generated sensor data is read and pushed to the data repository through KNX drivers. The simulated data is provided by the performance simulator, which uses weather data and occupancy counts from the cameras as inputs to simulate the building energy performance. The simulator is scheduled and configured automatically through an automation service in Java. Currently the simulator is scheduled to be executed on a daily basis, simulating the energy performance of the building for the last 2 weeks. The dashboard application deals with data streams from the centralized data repository. It first queries the data repository using an SQL-like syntax. Based on the resulting data it then calculates the energy performance and indoor comfort results. The calculated results are displayed on the user interface (UI), which is composed of gauge charts generated by dash_core_components library and updated through dash functions. The gauge charts for building energy performance are updated on a daily basis and the gauge charts for thermal comfort and indoor air quality are updated every 30 minutes.

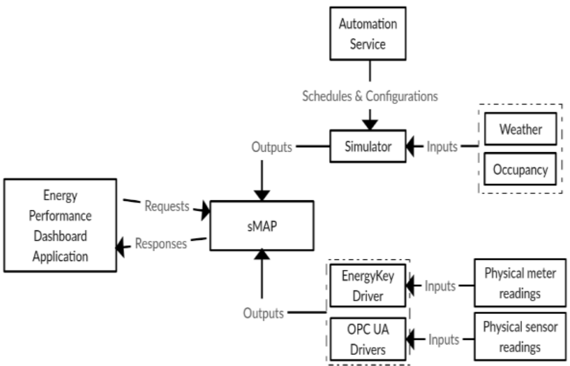

Figure 3: Dashboard application data interaction.

Building Energy Model Development and Calibration

Building Energy Modelling

A full-scale detailed dynamic building energy performance model was developed for the OU44 building case study, considering different building design specifications and characteristics including physical envelope properties, internal loads and schedules and technical energy systems. The holistic whole-building energy modelling and performance simulation developed by Jradi et al. (2018) was implemented in this case, employing a package of tools, SketchUp Pro, OpenStudio and EnergyPlus. An overall architectural 3D model of the building was developed first in Sketchup Pro providing an accurate representation for the different rooms and zones orientation and geometry within the building. The detailed 3D model was imported into OpenStudio where all the building envelope characteristics, energy supply systems properties, loads, schedules, weather conditions and occupancy patterns are defined and characterized. Openstudio allows linking the 3D model development details in SketchUp with the Energyplus tool, providing a user-friendly and flexible interface for the development of the holistic building energy model. The energy model developed in OpenStudio is later exported to an IDF file and introduced in EnergyPlus for additional features definition including setpoints, operational parameters and CO_2 sensors allocation. EnergyPlus was chosen for energy simulation as it is a free, validated, robust and well-documented energy modelling and simulation software. Figure 4 depicts a SketchUp Pro 3D model of the OU44 building. The resulting building model comprises 190 thermal zones over 3 floors and a basement with detailed representation of the building constructions and materials along with different energy conversion and supply systems including heating, ventilation, lighting, equipment and PV sub-systems.

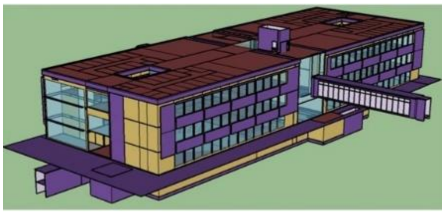

Figure 4: OU44 building 3D architectural model.

Energy Model Calibration

The whole OU44 building dynamic energy performance model presented in the previous section has been calibrated using actual collected data from the different energy meters and submeters in the building. This will ensure that the dynamic energy model can predict and simulate the energy performance of the building with a sufficient detail and acceptable accuracy. In addition, a calibrated dynamic energy performance model is a key factor in achieving effective building performance monitoring and evaluation process and establishing a systematic continuous commissioning process (Van Dronkelaar et al., 2016). The dynamic energy model is calibrated considering a period of 3 months from February to April 2018. This period was chosen as it has the full set of meter data required for calibration with no missing or corrupt data. In the calibration process, collected weather data from the weather station, occupancy counts from the 3D stereovision cameras and energy systems operational setpoints and parameters, including ventilation and heating units, are used as input along with the reported actual energy use. The occupancy profile generated based on the camera counts for the considered calibrated period is shown in Figure 5, with a reported maximum occupancy of around 930 people.

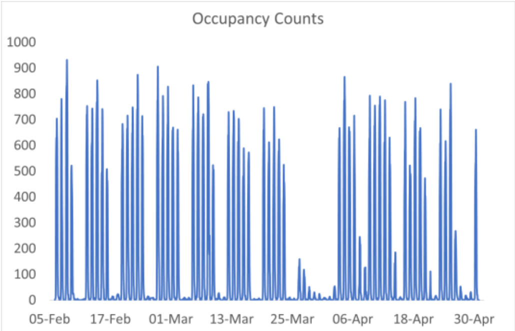

Figure 5: OU44 building overall occupancy counts from Feb to Apr 2018.

Using actual weather conditions, occupancy counts and systems operational parameters, the OU44 model was calibrated using Hale et al. (2014) suggested dynamic energy performance modelling calibration process. However, calibration using overall building energy usage for heating and electricity suggested was substituted by a more detailed calibration on the level of the individual energy supply systems, including ventilation units, lighting per floors, solar PV system and heating system. The main parameters selected for the dynamic model calibration include the space infiltration rates, pressure rise across ventilation units, fans, pump and equipment efficiencies in addition to loads and operation schedules. In terms of heating consumption, infiltration rates were found to be the parameters with the highest impact. Considering that the building complies with the Danish building regulation 2015 at the design stage, parameters set by the Danish BR15 were introduced in the calibration process with a set range of variation. Considering the different calibration parameters, a large number of simulations were considered and the scenario with the lowest deviation in terms of the individual energy systems consumption on a daily basis was chosen to be used as a basis for the continuous building commissioning and performance testing.

Figure 6 (a to d) shows the calibration process results comparing the actual and simulated energy use for (a) heating, (b) lighting and two selected ventilation units (c-d). In overall, the calibrated dynamic energy performance model was found to predict the actual building energy performance with an acceptable accuracy. The reported maximum deviation based on a daily level is -7.48% for the PV electricity supply, 5.94% for the ventilation units' electricity consumption, 1.38% for lighting electricity consumption per floor and -4.67% for the heating consumption. It shall be mentioned that a negative deviation characterizes a lower predicted energy use compared to actual numbers.

Automatic Building Performance Testing Implementation

The building automated continuous commissioning framework described earlier is implemented in the considered OU44 building case study aiming for building energy performance monitoring and evaluation. The calibrated building energy model is employed as a basis for the continuous building performance testing process, serving as an expected reference to compare and evaluate the actual performance on the level of the whole-building as well as the operation of the individual energy supply systems. Results from the dynamic energy performance model simulations are continuously and automatically used by the multiple performance tests as a baseline for comparison with actual data collected for the same period.

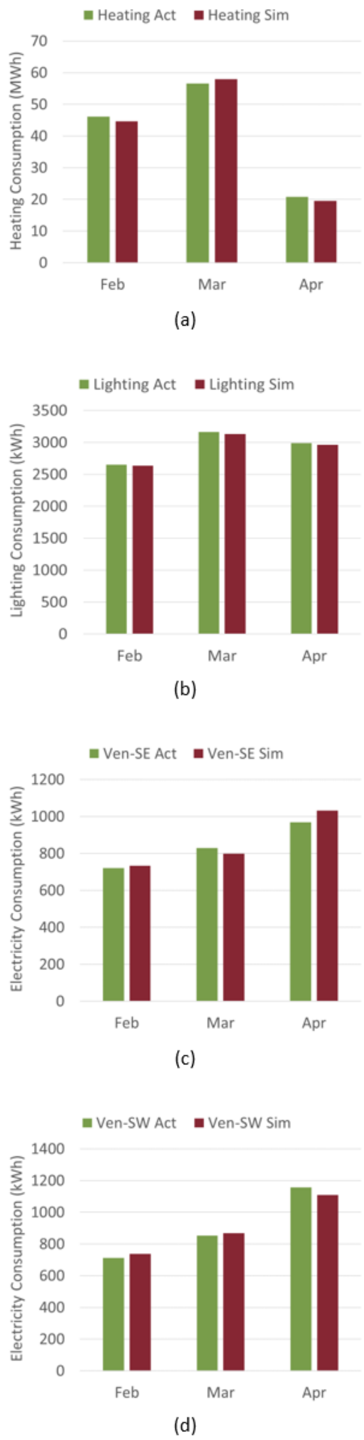

Figure 6: Actual vs Simulated energy use for monthly (a) heating, (b) lighting, (c) Southeast ventilation unit and (d) Southwest ventilation unit.

Based on the performance tests, a performance gap between the actual and the expected performance is reported in a continuous manner as well. The current implemented performance tests include:

1. Overall building heating consumption
2. Overall building electricity consumption
3. PV solar system electricity production
4. Electricity consumption for each ventilation unit
5. Lighting consumption in each floor

Monitoring the performance of the individual ventilation units and the lighting floor levels in addition to the overall heating and electricity consumption provides a more detailed view in terms of evaluation and analysis and allows for better and more accurate performance monitoring. The dynamic energy performance model uses collected weather conditions data, occupancy counts and systems operational setpoints to continuously and automatically simulate and predict the building energy performance on a daily basis. Regarding weather conditions, the weather station at the top of the building provides instant recordings for ambient temperature, wind speed and solar irradiation levels which are stored in the centralized data platform to be used in simulations. While the simulations are carried out every day, the dashboard platform developed shows the cumulative performance gap between the expected model simulations and actual building operation for the last 2 weeks, aiming to better characterise and evaluate the performance.

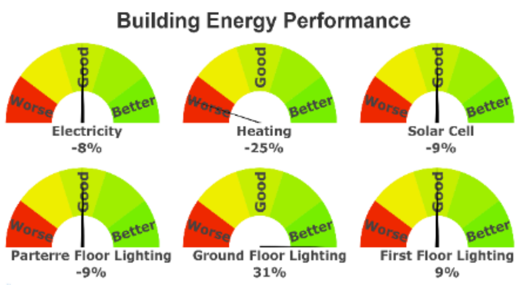

Figure 7: OU44 building overall energy performance in the first two weeks of May.

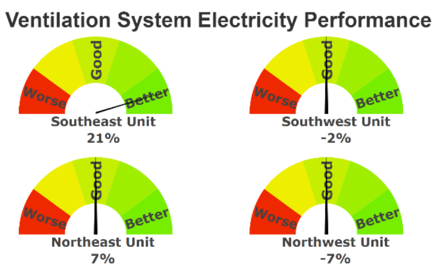

Figure 8: OU44 building ventilation units performance in the first two weeks of May.

Figures 7 and 8 show the performance testing results reported by the dashboard platform on May 14, covering the period from 1 to 14 May. Within this period, an acceptable performance of the building was reported as shown in Figure 7. The cumulative performance gap reported for the overall building electricity and heating consumption is -8% and -25% respectively. In addition, the performance testing of the solar photovoltaic system electricity production reports a cumulative performance gap of -9% for the considered 2 weeks. Regarding lighting electricity consumption, the dashboard platform shows the performance results of the lighting energy usage per floor, with a respective cumulative gap of -9%, 31% and 9% for the ‘Parterre’, ‘Ground’ and ‘First’ floors. In the current dashboard performance testing version, a performance gap exceeding ‘-20%’ to the left was considered to highlight a ‘worse’ condition. In addition, Figure 8 gives a more detailed insight on the performance of the individual ventilation units in the 4 building quadrants within the same period. The figure shows that there are some differences in the performance gap reported for the 4 ventilation units with a cumulative performance gap of 21%, -2%, 7% and -7% for the Southeast, Southwest, Northeast and Northwest ventilation units’ operation respectively.

While Figures 7 and 8 report the cumulative energy performance gap as a result of the OU44 building energy performance testing in the first two weeks of May 2018, a more detailed performance evaluation on a daily basis is carried out. Figures 9, 10 and 11 show the results of the building energy performance testing of the heating system, Southeast ventilation unit, and Southwest ventilation unit on a daily basis for the first two weeks of May. As depicted in the three performance monitoring figures, the heating system and the two ventilation units exhibit an acceptable performance compared to the expected simulation results reference.

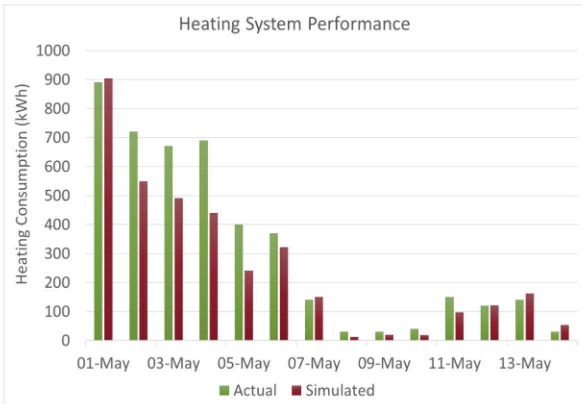

Figure 9: Heating system performance (Actual vs Simulated).

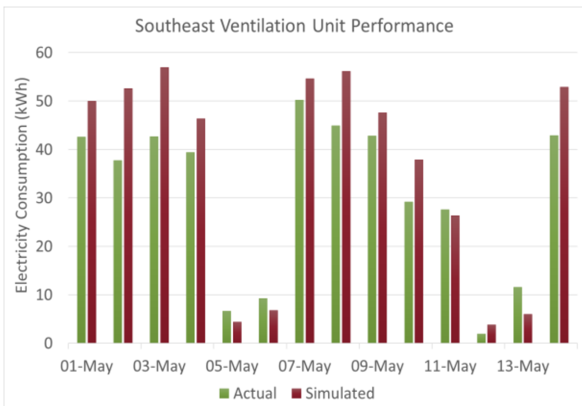

Figure 10: Southeast ventilation unit performance (Actual vs Simulated).

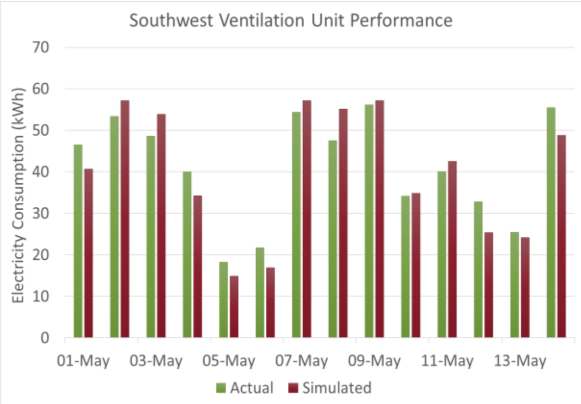

Figure 11: Southwest ventilation unit performance (Actual vs Simulated).

Considering the results provided for the first two weeks of May, the following daily evaluation and observations could be highlighted regarding the performance of the heating system and the two ventilation units:

1. High heating consumption during May 2-5.
2. Relatively low electricity consumption of the Southeast ventilation unit through the whole period.
3. Relatively high electricity consumption of the Southwest ventilation unit on May 1, 6, 12 and 14.

Reported Malfunctioning Ventilation Unit

The continuous building commissioning and performance testing framework developed is currently implemented and has been running in the OU44 building to automatically monitor and evaluate the overall building energy performance. As highlighted earlier, continuous building commissioning and performance testing is a major requirement for a systematic and effective fault detection and diagnostics process considering different energy conversion and supply systems operation. In this context, a specific case is reported in this study to highlight the added-value of implementing such approach in buildings, concerning a malfunctioning ventilation unit. Figure 12 shows the evolution of the cumulative performance gap reported regarding the operation of the Southeast ventilation unit in November 2018. As shown in the figure, the cumulative performance gap reported has drastically increased from -5% on Nov. 21 to -120% on Nov. 29. The negative sign characterises an actual energy use higher than the expected consumption. The spikes on 24 and 25 Nov. are due to being a weekend period with much lower expected consumption, and thus corresponding to larger performance gap as highlighted.

Considering these results, a more detailed investigation was carried out concentrating on the rooms supplied by the Southeast ventilation unit. It was found that one of the air diffusers in a large teaching room (U181) on the first floor, has a reported damper position of 100% (totally open), for most of the period from 21 to 29 November. As the air supply diffuser opening is driven by the CO_2 level in each room and a 100% opening corresponds to CO_2 level higher than 900 ppm, the CO_2 level in the U181 room was checked and a normal behaviour was observed with limited periods where CO_2 level exceeds 900 ppm.

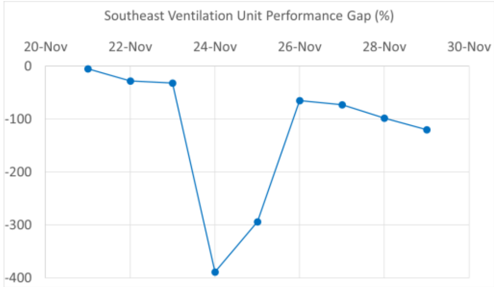

Figure 12: Southeast ventilation unit performance gap

An example of 29 Nov. is shown in Figure 13 where CO_2 level didn't exceed 900 ppm for the majority of the day, where the variable air volume (VAV) damper was fully open all day. Based on these findings, an alarm was issued to the technical services department. The technical services department reported that their investigation for the suspicious room has indeed found a problem with the VAV diffuser controller. Thus, the problem was resolved, and a normal operation for both the VAV damper and the ventilation unit was observed with a reported cumulative performance gap of -10.2% one week afterwards. The ventilation unit electricity consumption during the 2 weeks of malfunctioning was around 1260 kWh, in comparison to only 681 kWh in the previous 2 weeks of proper operation with an increase of around 84%. In addition to the technical added value of the automated continuous commissioning process in terms of supporting a systematic building fault detection and diagnostics, the average monthly avoidable operational costs due to eliminating this problem was calculated to be around 2664 DKK, (around 400 USD).

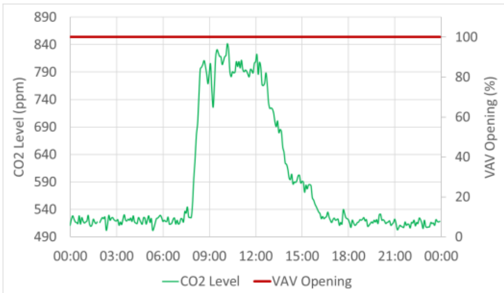

Figure 13: CO_2 level and VAV opening in room U181 on 29 November

Conclusion

In this study, a framework for automatic and continuous building energy performance monitoring and evaluation is presented, composed of a set of performance tests targeting different building energy subsystems. The core of the presented framework is a whole-building calibrated dynamic energy performance model providing a baseline for assessment. The automated performance tests serve as a basis for the continuous building commissioning aiming to better monitor, characterize and evaluate the performance on different levels. A case study of an energy efficient university building in Denmark is considered. A full-scale building energy performance model was developed in EnergyPlus and calibrated using actual weather data, occupancy counts from 3D stereovision cameras and operational setpoints. Employing the calibrated model, the automated continuous commissioning process was tested considering a period of 2 weeks in May, where performance testing results were visualized using a developed online dashboard platform. Finally, as part of the building fault detection and diagnostics, a specific case of a malfunctioning ventilation unit reported by the continuous commissioning process is presented. Based on the investigation, a fully-open VAV damper was noticed in one of the large teaching rooms for an extended period in November. This has led to around 84% increase in the electricity consumption of the ventilation unit in the malfunctioning two-weeks period. The problem was related to the logic of the corresponding VAV diffuser controller. After resolving the problem, a proper operation of the ventilation unit is reported with a cumulative performance gap of -10.2% a week later. The average monthly avoidable costs due to eliminating the problem was calculated to be around 2664 DKK. Although the framework presented in this study is implemented in a specific case study building, the framework is generic in principle and scalable to be applied in a wide range of buildings, with slight modifications regarding the performance tests considered to characterise the specific building energy systems. In addition, the manual work associated with the detailed model development will be reduced drastically with the evolution in the field of Building Information Model to Building Energy Model (BIM to BEM). Thus, a large amount of the information needed to be defined and characterized in the energy model development will be read and transferred from the available BIM, saving time and resources.

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

COORDICY Project (2015). Available from: http://www.sdu.dk/en/om_sdu/institutter_centre/centreforenergyinformatics/research+projects/coordicy

Dash (2018). Available from: https://dash.plot.ly.

Dawson-Haggerty, S., Jiang, X., Tolle, G., Ortiz, J., and Culler, D. (2010). sMAP, a Simple Measurement and Actuation Profile for Physical Information. *Proceedings from the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys10).* Zurich (Switzerland), 3-5 November 2010.

De Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction 41*, 40-49.

EnergyPlusToFMU (2018). Simulation Research Group - Lawrence Berkeley National Laboratory. Available from: https://simulationresearch.lbl.gov/projects/energyplustofmu

EU Commission (2010). Directive 2010/31/EU of the European Parliament on the energy performance of buildings, 2010.

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.

HOK (2016). Available from: https://www.hok.com/about/news/2016/05/26/hok-case-studies-reveal-short-payback-of-energy-modeling

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., Sangogboye, F.C., Mattera, C.G., Kjægaard, M.B., Veje, C., and B.N. Jørgensen (2017). A World Class Energy Efficient University Building by Danish 2020 Standards. *Energy Procedia 132*, 21-26.

Kim, J., Cai, J., and J.E. Braun (2018). Common Faults and Their Prioritization in Small Commercial Buildings:February 2017 – December 2017. *National Renewable Energy Laboratory (NREL) report*. Golden, CO, June 2018.

Markoska, E., Jradi, M., and Jørgensen B.N. (2016). Continuous commissioning of buildings: A case study of a campus building in Denmark. *Proceedings from the 9th IEEE International Conference on Cyber, Physical, and Social Computing (CPSCom 2016)*. Chengdu (China), 16-19 December 2016.

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.