

Calibration of a BES model of an educational building with demand controlled ventilation

Bart Merema¹, Muhannad Delwati², Maarten Sourbron², Hilde Breesch¹

¹Department of Civil Engineering, Construction Technology, KU Leuven - Technology Campus Ghent, Ghent, Belgium

²Department of Mechanical Engineering, KU Leuven, Leuven, Belgium

Abstract

A building energy simulation (BES) model of an educational building in Belgium, built according to the Passive House standard and equipped with demand controlled ventilation (DCV), is calibrated using real monitoring data. Measurements of room temperature, fan and heating power are used to calibrate the BES model. This calibration process involves a manual calibration based on an iterative approach. Results show that the simulation results fit within the set requirements for mean bias error (MBE) and coefficient of variation of the root mean square error (CvRMSE) for daily data. This calibrated simulation model is used to determine the energy saving potential of the DCV system compared to a constant air volume (CAV) system. DCV causes annual energy savings of 42% for fan energy use and 46% for heating energy.

Introduction

The energy needed for operation of ventilation systems in office and educational buildings is estimated to be 10-50% of the total energy consumption in buildings (EnBau, 2010). One way to increase energy efficiency is the implementation of a demand controlled ventilation (DCV) system which automatically adapts the air flow rates in relation to the actual ventilation demand, characterized by e.g., occupancy or CO₂ concentration. As a result, a significant decrease in the energy consumption for both the fans and heating can be obtained.

Following studies determined the energy reduction by DCV for office and educational buildings by simulation. Kaiser et al. (2015) simulated the energy savings for implementing a CO₂ controlled DCV system in an open office with a design flow rate of 525 l/s. The DCV system is coupled with active chilled beams which control the air flow rate by indoor CO₂ concentrations. The energy reduction for the fans, heating, cooling and pumps was 33-41% compared to a constant air volume (CAV). Lau et al. (2013) showed a reduction of 14,6% on the outdoor airflow by implementing a CO₂ controlled DCV by using a combined simulation model with EnergyPlus and EES. Furthermore, with a better controlling strategy of the variable air volume (VAV), reductions of 45% on the outdoor airflow were achieved in the same study.

This simulation model was built for a combined office/classroom building with a VAV system that controls the air temperature of the space. In another study by Sun et al. (2011), energy reductions by DCV was tested and simulated for a real multi-zone office building in Hong Kong. The DCV system was controlled by indoor CO₂ concentrations and indoor zone temperature. Energy reductions obtained by the CO₂-DCV were at minimum 52% for the fans and 42% for the cooling demand.

To make a reliable prediction of the energy savings potential of a DCV compared to a CAV system, the BES model has to be calibrated to detailed monitoring data of fan and heating power. Recent studies have shown the importance of calibration for BES models. Coakley (2012) showed that detailed building and HVAC system information could produce an accurate representation of the building by using hourly measured data. For calibration the mean bias error (MBE) and the coefficient of variance of the root mean square error (CvRMSE) are used as described in ASHRAE guidelines 14 (2002). In a recent study by Yang and Becerick-Gerber (2015) a BES model was calibrated for a multi-level building. In this study measured energy consumption for HVAC was compared to simulated energy consumption at building level and zone level. Results showed these values for MBE and CvRMSE were 8.5% and 13.5% respectively. Royapoor and Roskilly (2015) deployed a calibration study for a 5-storey office building by using hourly based measurement data. Values found for hourly MBE and CvRMSE were 5% and 10% respectively for gas and electricity load prediction. For air temperature the model demonstrated prediction accuracies of $\pm 1.5^{\circ}\text{C}$ for nearly 99,5% of hourly instances over the full annual cycle.

The goal of this research is to predict the energy savings of DCV compared to CAV in an educational building. For this purpose, a calibration of the BES model is needed. This paper describes the calibration process and result of this BES model. First the case study building is described. Afterwards, the BES model, method for and results of calibration are presented. Finally, the calibrated BES model is used to predict the annual energy saving potential of DCV compared to CAV.

Case study building

Building properties

The case study building is an educational building, built according to the Passive House standard, shown in Figure 1 and located in Ghent, Belgium (51N; 3E). The building is built on top of an existing university building and contains 4 zones: 2 large lecture rooms, a staircase and a technical room. The lecture rooms have a floor area of 140 m², a volume of 380 m³ and a maximum capacity of 80 students each. A floor plan and a cross section of the building are shown in Figure 2 and 3. The building is used as normal lecture rooms but at the same time it is a test facility for research on building energy-efficiency strategies in a “real use” environment. Therefore, the lecture rooms are thermally insulated from the outside, the neighbouring zones and each other. The U-value of the construction parts are shown in Table 1. The solar heat gain coefficient for the glazing is 0,52. The window to wall ratio is 26% for NE and 27% for SW façade. Air tightness at 50 Pa of the lecture rooms is 0,29 1/h for the first floor and 0,47 1/h for the second floor. Moveable external blinds are applied on the windows on the southwestern side. Blinds are closed when the incident solar radiation exceeds 250 W/m². More information about the design process can be found in Breesch et al. (2016).

Table 1; U-value of building construction

Construction part	U-Value (W/m ² K)
Wall	0,14
Roof	0,14
Floor	0,15
Glazing (glazing)	0,60
Glazing (frame)	0,90

HVAC properties

A demand controlled, balanced mechanical ventilation system is provided with an air-to-air heat exchanger (efficiency is 78%) and VAV boxes placed in the supply and extract openings in each room controlling the air flow rate based on CO₂-concentrations and temperature in the lecture rooms. The maximum air flow rate per room is set at 2200 m³/h and the minimum at 400 m³/h. Two heating coils of 8 kW are integrated in the supply ducts. The heating production system consists of a condensing wood pellet boiler with an internal storage of 600 l. The maximum heating power is 8 kW and the maximum efficiency is 106 %. A supply fan is installed with a maximum power of 1,57 kW and 1,33 kW for the extraction fan with an efficiency of 71%. Efficiency of the fan motors is 85%. Indirect evaporative cooling (IEC) with a maximum capacity of 13.1 kW is provided.



Figure 1; Outside view of the educational building

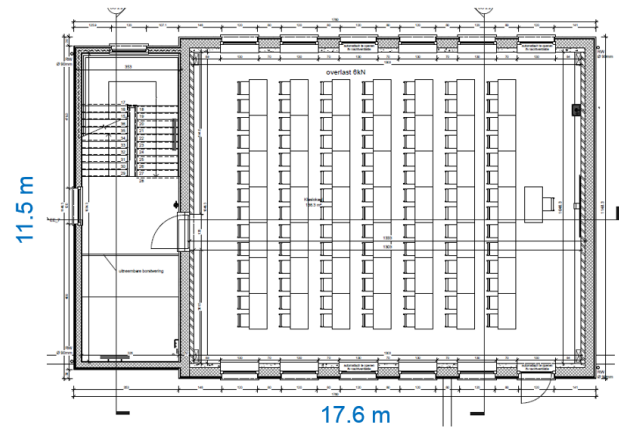


Figure 2; Floor plan of one lecture room

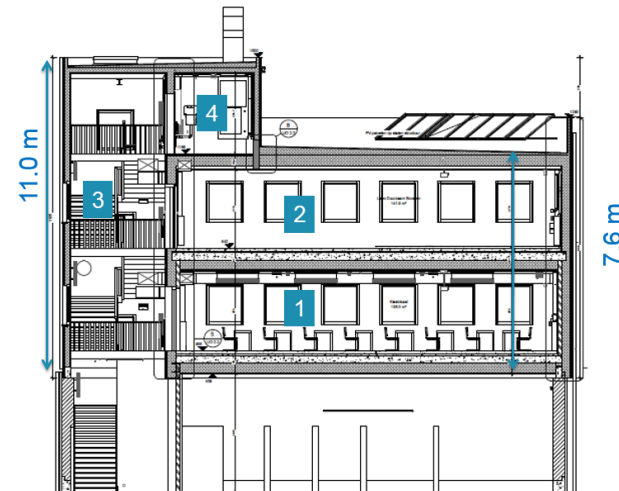


Figure 3; Cross-section of the building (1) lecture room (2) lecture room (3) staircase (4) technical room

Use and control

The lecture rooms are used during the academic year, which counts 124 days with courses and 63 days with exams (in January, June and August-September). Holiday periods are in April (2 weeks), July and the first half of

August (6 weeks) and December-January (2 weeks). The lecture rooms are in use from Monday to Friday between 8h15 and 17h30 with a maximum occupancy of 80 persons. The actual occupancy during the measurement period is shown in Figure 6.

The air handling unit (AHU) is operating from 07:30-17:30h during weekdays. The CO₂ setpoint for the DCV system in use is set at 1000 ppm, which corresponds to IDA class 3 with an air flow of 28 m³/h.pers (EN 13779, 2010) or 16 m³/(h.m²). The heating setpoint for the heating system is set at 21°C. There is a deadband active of $\pm 0,5^{\circ}\text{C}$ on the heating setpoint. Standby temperature during non operating hours is set at 15°C. Minimum supply temperature is 15°C. The air flow rate and/or supply temperature is increased when one of these setpoints are not met. The heat exchanger is bypassed when the outdoor temperature is above 16°C or when the room temperature in one of the lecture rooms exceeds 22.8°C. IEC is activated when the room temperature exceeds 26°C and continues till the room temperature is lower or equal to 20.5°C.

Monitoring

A set of sensors has been installed to monitor indoor and outdoor conditions and is described in Andriamamonjy and Klein (2015). The building has its own weather station which monitors the main outdoor parameters: global horizontal solar radiation, the outdoor temperature, relative humidity and the wind speed and direction. For the indoor conditions, the indoor temperature, the CO₂ concentration and the indoor humidity are continuously monitored. The occupancy of the lecture room is measured by using pictures from cameras which were installed in the lecture room taking pictures on an 5 minute time interval.

Simulation

For the integrated dynamic simulations, EnergyPlus (EnergyPlus 2015) and DesignBuilder (Designbuilder 2015) are used. For the weather data, outdoor dry bulb temperatures, relative humidity and incident horizontal solar radiation are monitored by an in-situ weather station. A script is used for the transformation of global horizontal solar radiation into direct normal and diffuse solar radiation based on the methods described by Perez et al. (1992) and Maxwell (1987). This data is used to create a weather file with the local air temperature, relative humidity, diffuse solar radiation and direct normal radiation. IR radiation is calculated (Walton, 1983) (Clark and Allen, 1978) in EnergyPlus using the sky covering which is collected from the weather station of Uccle.

In the BES model, the walls to the staircase and the floor to the ground floor are assumed to be adiabatic. The simulation is started six weeks prior to the calibration period to heat up the building to take into account the

thermal mass of the building construction. The convective heat transfer coefficient (CHTC) for the building construction is calculated using the adaptive convection algorithm included in EnergyPlus. This advanced option uses the CHTC by implementing the equations from research by Beausoleil-Morrison (2000). The set point temperature used for the heating is set at 21.5°C to include the deadband effect of $\pm 0.5^{\circ}\text{C}$. The CO₂ generation rate per person is set at 0.31 l/min, according to ASHRAE Standard 62.1 (2007).

The control of the DCV system is modelled as shown in Figure 4, using an energy management system (EMS) script in EnergyPlus.

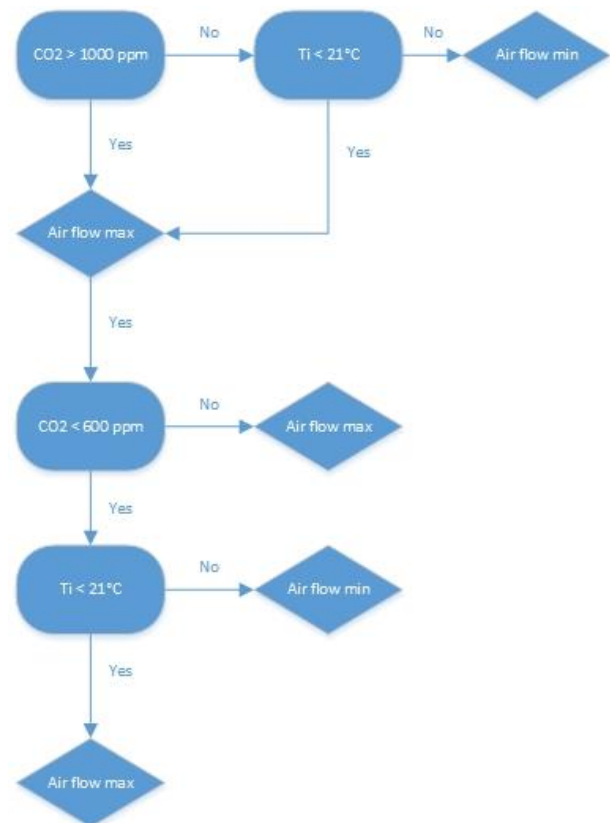


Figure 4; Control of DCV system for simulation

The internal heat gains, shown in Table 2, only consider gains from people and lighting in the lecture rooms. The radiant fraction of gains from persons is set at 0,30.

Table 2; Internal heat gains

Source	Internal heat gains
Lighting	1100 W/room
People	110 W/person

Calibration

Buildings do not usually perform during operation as well as predicted during the design stage. Disagreement between simulated and metered energy consumption represents a common issue in building simulation. For this purpose, calibration of the BES model is needed.

Method

The process of calibration in this research involves a manual calibration based on an iterative approach. This includes trial and error approaches to manually tune model input parameters based on knowledge about the building and user experience. To set up the calibration model, the following steps are performed: (i) set up geometry of the building, (ii) assign thermal properties to the construction, (iii) add air and heating loop and connect them to the modeled building zones, (iv) define properties and control algorithms according to the as-built file for all modeled HVAC system parts, (v) assign activity schedules for equipment and occupancy, (vi) error check, (vii) test criteria for calibration, (viii) trial and error of calibration if criteria are not in agreement.

The calibration process is performed according to the ASHRAE Guideline 14 (2002), IPMVP (2012) and M&V guidelines for FEMP (2015). These guidelines use the mean bias error (MBE), given in equation 1, and the coefficient of variation of the root mean square error (C_vRMSE), shown in equation 2-4, to assess the uncertainty of the simulation data compared to monitoring data.

To calibrate the model, monitoring data of room temperature and energy use, logged on a one-minute time interval by the building monitoring system (BMS) is used. Requirements for the MBE are $\leq 10\%$ for hourly data and for the $C_vRMSE \leq 30\%$ for hourly data. For monthly data the requirements are respectively ≤ 5 and $\leq 10\%$. Since for daily data no requirements are specified in the guidelines the same requirements as for hourly data are used.

$$MBE (\%) = \frac{\sum(S-M)_{interval}}{\sum M_{interval}} * 100 \quad (1)$$

$$RMSE_{period} = \sqrt{\sum \frac{(S-M)_{interval}^2}{N_{interval}}} \quad (2)$$

$$A_{period} = \frac{\sum M_{interval}}{N_{interval}} \quad (3)$$

$$C_vRMSE (\%) = \frac{RMSE_{period}}{A_{period}} * 100 \quad (4)$$

S = Simulated data

M = Measured data

N = Number

The following parameters of the system will be calibrated during the fine-tuning process:

- Building
 - Air tightness
 - Capacity of the furniture in the zone
- System
 - Fan power (supply and extract)
 - Room thermostat (air/radiant temperature)

Preliminary results are shown to present the impact of these parameters.

Monitoring data

For the calibration of the model, one minute measurement data for the period of 18-29 of April 2016 are used. More monitoring data are presented in Merema, et al. (2015). The outdoor temperature during the measurement period as shown in Figure 5 was minimum 2°C and maximum 20°C. The outdoor CO₂ concentration, which was measured, is set at a constant value of 450 ppm. The occupancy profile of the week from 18-22 of April is shown in Figure 6. In this week, the lecture room is used for approximately 30 hours. The maximum number of people present was 60 and a minimum of 12 during the calibration period.

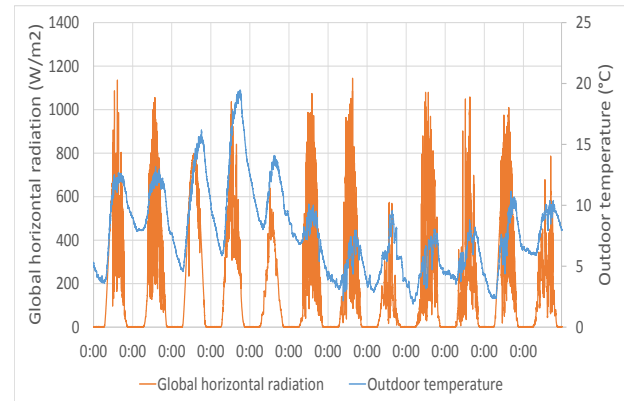


Figure 5; Outdoor weather conditions during measurement period 18-29th of April 2016

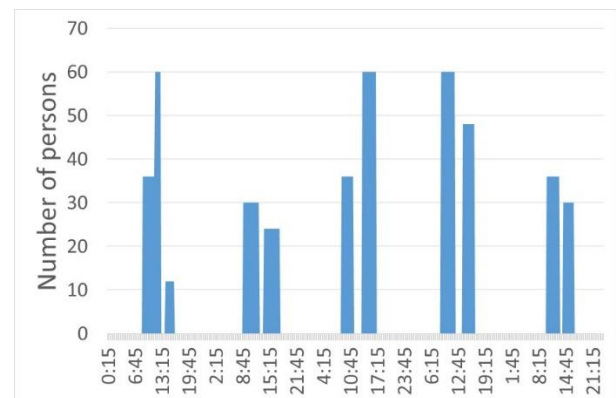


Figure 6; Actual measured occupancy of lecture room

Results and Discussion

Calibration process

First run of simulation consists with the building data as given in the description of the case study building. However, the first attempt (Simulation 1) in Figure 7 show that the decay of room temperature during the weekend inside the building zone was overestimated. The decrease in temperature in the first hours after the AHU is switched off at Friday (17:30h) is too large. Differences with measured values are at maximum 1,10°C, which is outside the accuracy range of the sensor (i.e. 0,50°C). For this purpose, the capacity of the air (from 1 to 5) is increased to take into effect the capacity of furniture. Altering the value for the air capacity resulted already in better agreement (Simulation 2) with the measurement values, however, the differences are still too large (1°C) after 2 hours. In addition, the air tightness is increased, tests have been performed to assess the current air tightness of the lecture room. Results of the new air tightness test resulted in an air tightness of 1,0 1/h at 50 Pa. This updated data is implemented in the rerun of the simulation file to check if the temperature decay is in agreement with the measured values. The final result (Simulation 4) showed good agreement with the measured values, differences were at maximum 0,40°C which is within the accuracy range of 0,50°C of the temperature sensor.

For the first test with the criteria the following parameters will be tested for the calibration of the model: Fan power and heating coil power. Since the first results, shown in Table 3, are not in agreement with the criteria specified in the ASHRAE guidelines the fan power curve is adjusted to approach the criteria for the fan power. The polynomial coefficients are used for the calculation of fan power at partial load (equation 5) in order to include the pressure losses in the ducts and VAV boxes and to maintain a constant pressure towards the end of the main duct. In the first scenario the MBE, with the default values as given in EnergyPlus for the fan, is too high to meet the requirements. This is mainly caused by too high fan power at low air flows compared with measurements. Therefore, the coefficients have been changed by using polynomial coefficients as proposed by Schild and Mysen (2009) and from data of fan power measurements performed on the AHU previously (Merema, 2015), so the normalized fan power curve is known. From these two sources the final adjusted polynomial coefficients are determined and implemented in the Fan adjust scenario.

$$PLF = 0.29 - 0.88 * FF + 1.99 * FF^2 - 0.40 * FF^3(5)$$

PLF = power load fraction

C1-C4 = polynomial coefficients

FF = flow fraction

The adjusted polynomial coefficients (50/50 Fan adjust) shows improvements for the MBE for the fan, which is now within the predefined agreements of the ASHRAE

guidelines 14. However, still the CVRMSE is too large to meet the requirements. Furthermore, it is shown that the heating coil is affected by the adjusted polynomial coefficients.

Finally, the last parameter that is adjusted during the calibration process is the thermostat of the room. The values for the heating coil are still not in agreement and underestimated by the simulation model, indicated by the negative MBE value. This suggests that the thermostat in the building is more affected by air temperature than radiant temperature. For this fine-tuning the thermostat is adjusted from 50/50 air/radiant to 60/40 air/radiant. Results in Table 3 indicates that simulated values are still not in agreement with measured values. In the last step the thermostat is changed to 80/20 air/radiant. Adjusting these parameters show better agreement with the results, which is displayed in Table 3.

Table 3; Results for MBE and CVRMSE during the calibration process

		50/50 Fan default	50/50 Fan adjust	60/40 Fan adjust	80/20 Fan adjust
Fan	MBE	15,4	-0,6	1,7	2,8
	CvRMSE	35,9	33,8	30,2	27,3
Heating coil	MBE	-6,0	-6,4	-7,0	0,1
	CvRMSE	37,4	45,2	31,2	31,7

Final results

Measured and simulated data of heating power, fan power and room temperature are compared for the lecture room on the second floor. Figure 8, depicts the temperature comparison. The maximum difference between measurements and simulations is 1°C. The decrease in room temperature after the AHU is switched off, (during night) shows differences of approximately 0,50°C at maximum. These results show a good agreement between simulated and measured room temperature.

The MBE for fan power, which is the total power for the supply and extract fan for one lecture room, is 2,80% and the CvRMSE is 27,30%, which is still within the predefined requirements. Deviations are mainly found during maximum air flow with differences of 400 W. However, the MBE shows that for the total period the agreement of the simulations with the measurement data is good. This is also shown in Figure 9. For heating power of the heating coil, the MBE is 0,11% and the CvRMSE is 31,70%. This CvRMSE exceeds the requirement with a small amount and is caused by some large deviations in power use for heating on the third day as shown in Figure 10. This is due to the bypass operation of the system. For simulations the bypass is set at 22,8°C however, sometimes in measurements it is shown that the bypass is activated at a lower or higher temperature. The temperature of 22,8°C is an average value.

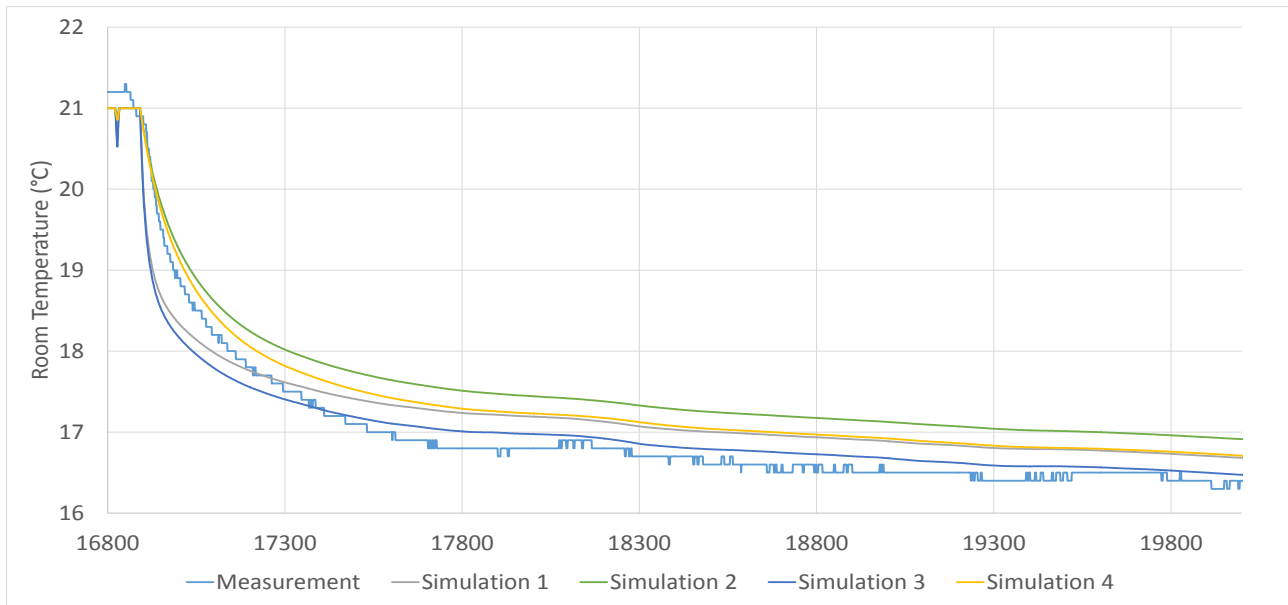


Figure 7; Fine-tuning air tightness and capacity of furniture

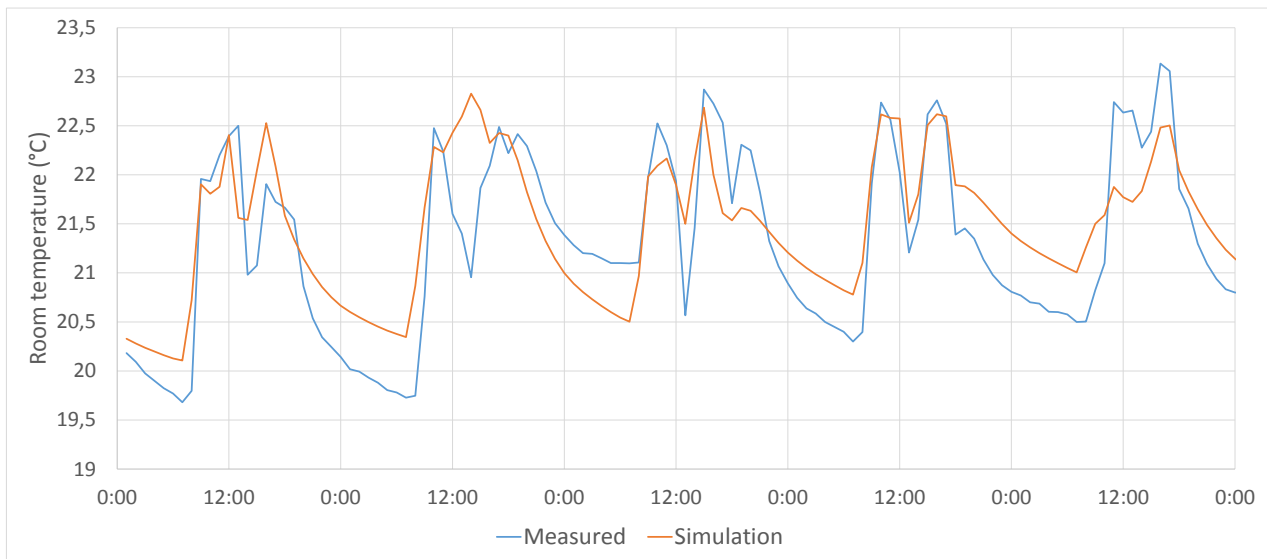


Figure 8; Measured and simulated data for room temperature 18-22 April 2016

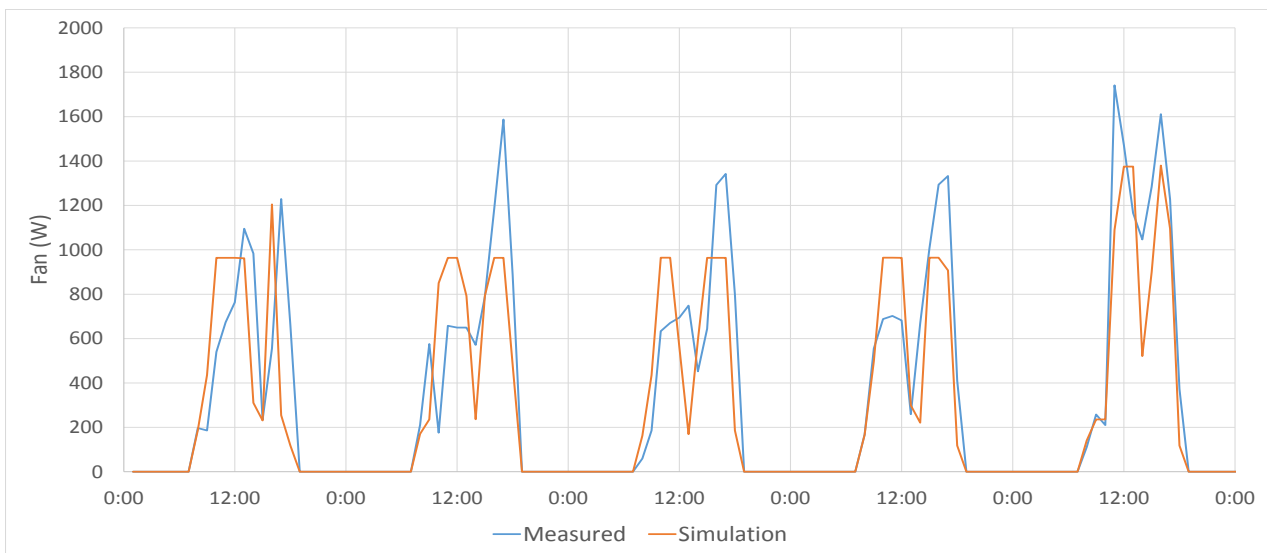


Figure 9; Measured and simulated data for fan power 18-22 April 2016

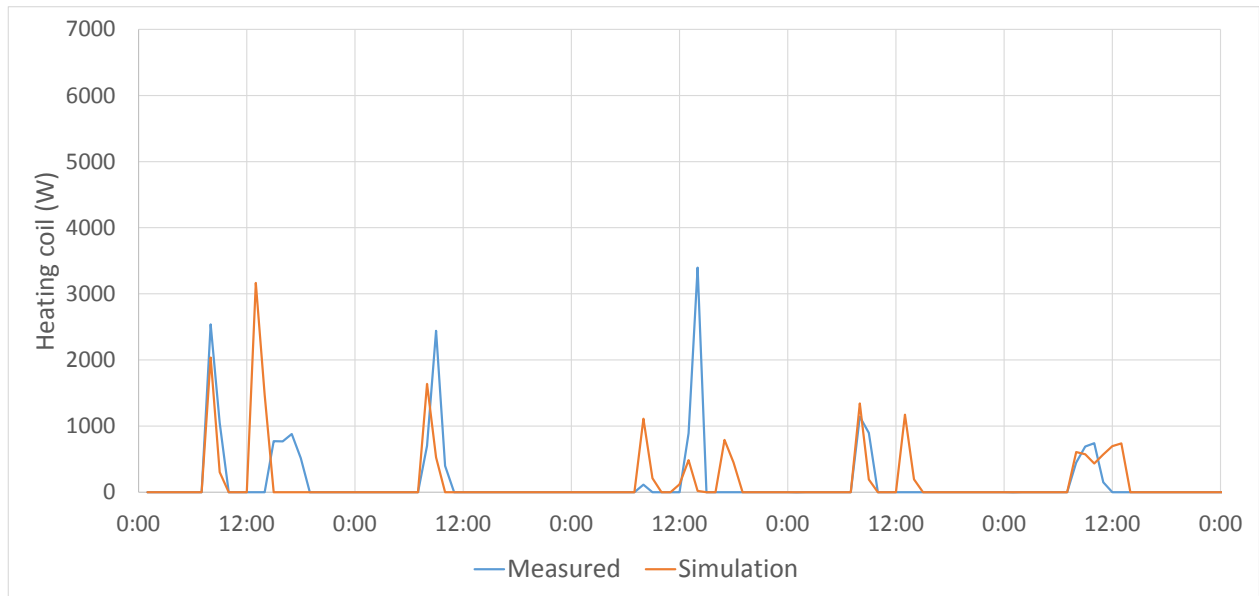


Figure 10; Measured and simulated data for heating coil 18-22 April 2016

Finally, the deadband operation of the heating system could not be simulated exactly in EnergyPlus. In addition, the reaction time for heating coils of the simulation is faster compared to the measurements which can cause higher heating loads during a short period.

Table 4, shows the total energy consumption for the fan and heating coil during the period of 18-29th of April 2016 for one lecture room. It shows that the total energy consumption for both measurements and simulations is comparable with differences of 1-3%. The MBE for heating and fan power showed that the difference between measurement and simulation is small which results in a good agreement for energy consumption.

Table 4; Energy consumption during calibration period 18-29 April 2016

	Energy consumption measured (kWh)	Energy consumption simulated (kWh)
Fan	57,0	58,6
Heating coil	44,9	45,0

Overall, it must be considered that the response time for the system in simulation is much faster compared to the measurements which can cause large deviations for power use for both the fans and heating coil resulting in a higher CvRMSE.

Strengths and weaknesses of the calibration process

The strengths of this calibration are:

- Availability of BMS data with 1 minute time-interval of all building/system parameters, local weather station and detailed occupancy data so extensive

- Measurement data is used for building the calibration model
- Calibration of a BES model of both building and system
- Calibrated model shows good agreement so it can be used for further sensitivity analysis
- Hourly or daily resolutions show better the deviations for the power use/consumption compared to monthly resolution

The weaknesses of the calibration are:

- Only two successive week of reliable monitoring data
- Operation of IEC is not included in the calibration
- Differences between real performance and simulation that cannot be solved, like the operation deadband heating setpoint is not included in the simulation, instead a fixed setpoint is used. In simulation, also high supply temperatures and flows are possible in a short time interval, however in realtime there is always a lag between demand and delivery
- Hourly data are more difficult to calibrate for system parameters regarding the CvRMSE (power fan and heating coil), due to this response time and lag
- Data from the as built situation that were not reliable, e.g. air tightness, operation of the bypass of the heat exchanger

Prediction energy savings potential DCV

Once calibrated, the BES model is used to assess the energy performance of a DCV system. The energy saving potential is determined by comparing the simulated energy consumption of a DCV system to the results of a CAV system with a design flow rate 2200 m³/h. An annual simulation is performed to analyze the actual energy

performance for the DCV system. For this annual simulation some assumptions had to be made regarding occupancy profile and AHU operation time. For the occupancy profile, the week profile of the calibration period is extrapolated to a complete year. For the use of the classroom the academic calendar has been used to take into account the holidays and exam periods. For both lecture rooms the same occupancy profile is used. For the weather data climate file of the nearest weather station in Uccle (Belgium) has been used. With Meteonorm 7 (Meteotest, 2016) a climate file is generated which can be used in EnergyPlus. Timestep used for the annual simulation is 3 minutes.

The annual end energy used of the DCV system for heating is 15 kWh/m².a and for fan use is 17 kWh/m².a. Compared to a CAV system, the savings caused by DCV are 46% for heating energy and 42% for the fan power consumption for a whole year. For the annual simulation, the lecture rooms are in use for 1200 hours each. Total operation time of the AHU is approximately 1800 h/a. Simulated operation of the DCV system is shown in Figure 11. The air flow responds well to the predefined CO₂ setpoint of 1000 ppm. However, some differences are noticed in air flow between simulation and measurements. On the first day, the air flow in the afternoon is not set at maximum in simulation while in measurements it is shown that there is a maximum air flow. This is due to the difference in CO₂ concentrations between measurements and simulations. The simulated CO₂ is just below the setpoint, 980 ppm, and the measured CO₂ is slightly above 1000 ppm causing a difference in air flow. Furthermore, the response of increasing air flow is faster in simulations

than in the measurements resulting in lower peaks of CO₂ concentration. These results show that reductions for the implementation of a DCV can be significantly for both heating and fan energy consumption compared to a CAV system.

Conclusion

For an educational building with a DCV system a simulation model is calibrated with use of real monitoring data. The calibration process showed that fine-tuning using an iterative approach for the parameters: air tightness, capacity of furniture in the zone, polynomial coefficients of the fan and room thermostat resulted in an accurate BES model. A good agreement is shown between the simulations and the measurements. The simulated data of fan and heating power fit within the set requirements for hourly calibration data $C_v\text{RMSE} \leq 30\%$ and $\text{MBE} \leq 10\%$. The calibrated model is used to compare a DCV system with a CAV system regarding the energy reduction for both heating and fans. Results show that savings are 46% for heating energy and 42% for the fan power consumption for a whole year.

Acknowledgements

This research is funded by Flanders Innovation and Entrepreneurship (VLAIO). This support is gratefully acknowledged. TETRA 140345: “Optimisation of demand controlled ventilation in nZEB commercial buildings”

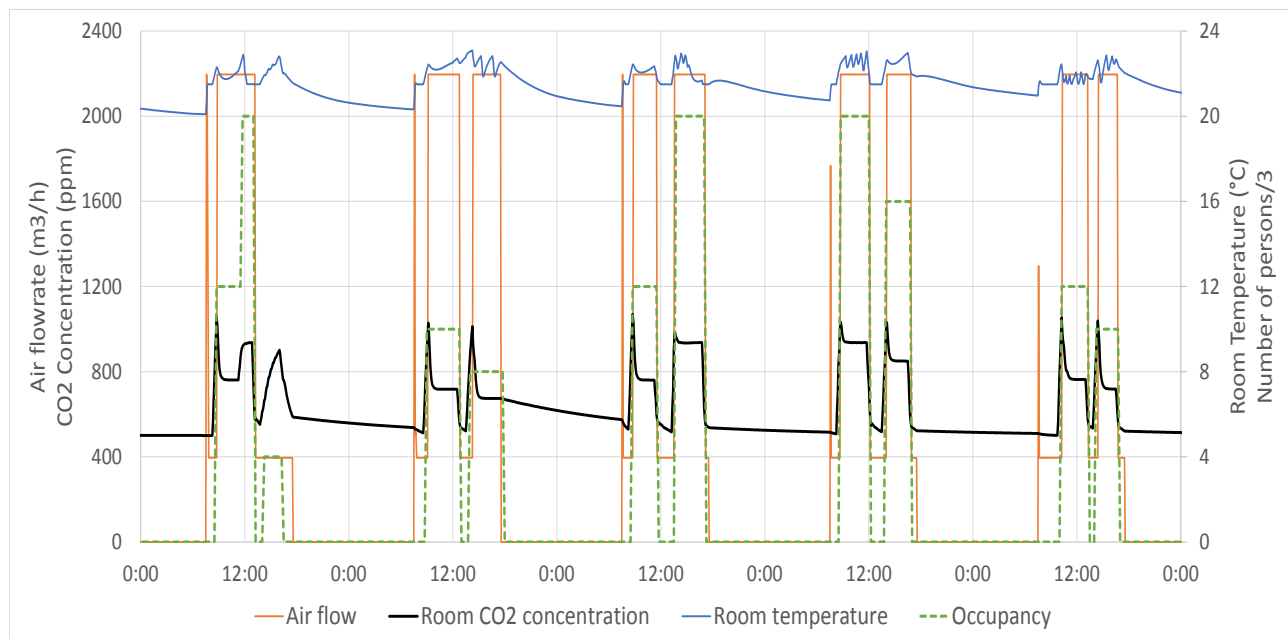


Figure 11; Simulated air flow, indoor CO₂ concentration, occupancy and room temperature for annual simulation

References

- Andriamamonjy, R., Klein, R., (2015). A modular, open system for testing ventilation and cooling strategies in extremely low energy lecture rooms, *36th AIVC Conference*, Madrid, 2015
- ASHRAE (2002). ASHRAE Guideline 14: Measurement of Energy Demand and Savings
- ASHRAE Standard 62.1 (2007) Ventilation for Acceptable Indoor Air Quality, Health Care 1-4
- Beausoleil-Morrison, I., (2000). The adaptive coupling of heat and air flow modeling within dynamic whole-building simulations. PhD Thesis. University of Strathclyde, Glasgow, UK.
- Breesch, H., Wauman, B., Klein, R., Versele, A., (2016). Design of a new nZEB test school building, *The REHVA European HVAC Journal* 53 (1), 17-20
- Clark, G. and C. Allen, (1978). The Estimation of Atmospheric Radiation for Clear and Cloudy Skies, *Proceedings 2nd National Passive Solar Conference (AS/ISES)*, 675-678.
- Coackley, D., Raftery, P., Molloy, P. (2012). Calibration of whole building energy simulation models: detailed case study of a naturally ventilated building using hourly measured data. *First building simulation and optimization conference*, Loughborough, 2012
- DesignBuilder (2015). Software. Version 4.3. DesignBuilder Software
- EnBau (2010). Performance of buildings across the year. Accessed July 2016 <<http://www.enob.info/en/analysis/analysis/details/performance-of-buildings-across-the-year/>>
- EnergyPlus (2015). Software. Version 8.3. US Department of Energy.
- FEMP (2015). M&V Guidelines: Measurement and Verification for performance-based contracts version 4.0
- IPMVP (2012). New Construction Subcommittee. International Performance Measurement & Verification Protocol: *Concepts and Option for Determining Energy and Water Savings Volume 1*
- Kaiser, A., Kurnitsku, J., Sormunen, P. (2015). Demand controlled ventilation indoor climate and energy performance in a high performance building with air flow rate controlled chilled beams, *Energy and Buildings* 109, 115-126
- Lau, J., Lin, X., Yuill, G. (2013). CO₂ based demand controlled ventilation for multiple zone hvac systems, *ASHRAE research project report 1547-RP*
- Maxwell, E. L (1987). A Quasi-Physical Model for Converting Hourly Global Horizontal to Direct Normal Insolation, *Technical Report No. SERI/TR-215-3087*, Golden, CO: Solar Energy Research Institute, 1987
- Merema, B., Breesch, H., Sourbron, M., Verplaetsen, J., Van den Bossche, P., (2015). Demand controlled ventilation in practice: Case study, *36th AIVC Conference*. Madrid, 2015
- Meteotest (2016) Software. Version 7.1.8. Meteotest Genossenschaft
- Perez, R., P. Ineichen, E. Maxwell, R. Seals and A. Zelenka, (1992). Dynamic Global-to-Direct Irradiance Conversion Models, *ASHRAE Transactions-Research Series*, pp. 354-369
- Royapoor, M., Roskilly, T., (2015). Building model calibration using energy and environmental data, *Energy and buildings* 94, 109-120
- Schild, P.G., Mysen, M., (2009). Recommendations on specific fan power and fan system efficiency, *Technical Note AIVC* 65
- Sun, Z., Wang, S., Ma, Z., (2011). In-situ implementation and validation of a CO₂-based adaptive demand-controlled ventilation strategy in a multi-zone office building, *Building and environment* 46, 124-133
- Walton, G. N., (1983). Thermal Analysis Research Program Reference Manual. NBSSIR 83-2655. National Bureau of Standards, p. 21.
- Yang, Z., Becerick-Gerber, B., (2015). A model calibration framework for simultaneous multi-level building energy simulation, *Applied Energy* 149, 415-431