Simulation of control strategies for ventilation systems in commercial buildings

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ABSTRACT

By the end of 2020 all newly constructed buildings have to be nearly zero energy buildings (nZEB). In school and office buildings the ventilation system has a large contribution to the total energy use. A smart control strategy that adjusts the operation of the ventilation to the actual demand can significantly reduce this energy use. Consequently, control systems are becoming an important part of the ventilation system in these nZEB buildings. To make an accurate prediction of the operation and energy consumption, building energy simulation (BES) programs need to include detailed control strategies. In most simulation programs the dynamics of the HVAC systems are difficult to implement since idealized controllers are used in the component model. The aim of this paper is to study the implementation of control strategies in different BES environments and to identify the effect of control of the ventilation system on the energy use and indoor climate (i.e. temperature and CO_2).

For this research, an all air ventilation system in an existing university building is studied. The building consists of two lecture rooms, each with a capacity of 80 students. Balanced mechanical ventilation is provided with a total supply airflow of 4400 m³/h. The airflow rate is controlled by VAV boxes based on measurements of CO_2-concentration and temperature in each lecture room. In this building, a building monitoring system (BMS) logs the data for all the parameters, e.g. room temperature, air flow, CO_2 and energy use, on a one-minute time interval. Furthermore, global horizontal solar radiation and outdoor temperature data from the weather station on the existing building is used as input data.

The BES model is set up in Modelica. The results of the simulation model is compared to an already calibrated model created with Designbuilder/EnergyPlus and measurement data. The implementation of the control strategy in both Modelica and EnergyPlus is compared to show the differences and possible limitations. This comparison shows that both Modelica and EnergyPlus enable the functionality to implement a smart control strategy for ventilation systems commonly found in commercial buildings. The results show that the IEQ and indoor temperature could be controlled as measured in the case study building. However, Modelica is a useful simulation tool to include a more complex control for HVAC systems compared to EnergyPlus. In contrast, EnergyPlus does not include detailed control for P, PI and PID control. In order to simulate these effects the BES tool needs to include the dynamics for these components. Since the impact of control in nZEB buildings on the total energy consumption is more significant. Modelica is a good option to include a more complex control for HVAC systems compared to EnergyPlus, since it allows to control the dynamics of the dampers and valves. However, EnergyPlus is still a useful and powerful and accurate BES software to calculate energy consumption.

KEYWORDS
Building energy simulation, ventilation, indoor air quality, control strategies, commercial buildings

1 INTRODUCTION

By the end of 2020 all newly constructed buildings have to be nearly zero energy buildings (nZEB) according to the new EPBD 2016 regulations. 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). A smart control strategy that adjusts the operation of the ventilation to the actual demand can significantly reduce this energy use. Measurements have shown the actual performance of demand controlled ventilation (DCV) in buildings (Merema et al. 2018). Consequently, control systems are becoming an important part of the ventilation system in these nZEB buildings. To make an accurate prediction of the operation of the building and its systems, building energy simulation (BES) programs need to include detailed control strategies. In most BES programs the dynamics, opening time for dampers and valves, of the HVAC systems are difficult to implement (e.g. VAV damper controlling both CO_2 and temperature) since idealized controllers are used in the component model (Wetter 2009).

A simulation tool that enables the ability to include more detailed control of systems is Modelica. Modelica is an object oriented equation based language allowing simpler schematic modelling and generating code for both simulation and optimization (Wetter, Bonvini, and Nouidui 2016). Open source libraries have been developed to include components inside Modelica for modelling buildings and HVAC systems. One of the available libraries is IDEAS, integrating both building envelope and HVAC systems as well as electric system simulations (Baetens et al. 2012, 2015). Recently the focus of the development of IDEAS is on detailed simulations at the building level since building systems have become more complex. (Jorissen, Reynders, et al. 2018) demonstrates that the accuracy of a BES model created in Modelica using the IDEAS library is comparable to EnergyPlus models based on BESTEST series 600 and 900 regarding results for heating and cooling loads. A second library that is developed is the Buildings library (Wetter et al. 2014). This library offers the ability to implement component and system models for building energy and control systems inside Modelica.

Furhtermore, most BES tools is that pressure drops in airflow networks are neglected or modelled as a function of the mass flow rate. In most cases the air flow rate is used as an input for HVAC components. Modelica includes pressure-driven airflow networks. To construct these networks in Modelica in a fast and efficient manner a comprehensive overview is given by Jorissen, Wetter, and Helsen (2018), presenting solutions to reduce the number of equations in Modelica. In addition, developments have been made to reduce the computation time for Modelica models by simplifying equations resulting in a simulation time 500 times faster than the real time (Jorissen, Wetter, and Helsen 2015).

The aim of this paper is (1) to study the possibilities for implementation of control strategies in both Modelica and EnergyPlus/Designbuilder, and (2) to identify the effect of control for the ventilation system on the energy use and indoor climate. The outline of this paper is as follows, first the case study is presented and the used approach is given. Following is the approach of implementing the ventilation system in both Modelica and EnergyPlus with the accompanying results. Afterwards, the effect on the indoor environmental quality (IEQ) and energy consumption is shown. Finally, a conclusion is presented for the study.

2 METHOD

2.1 Case study Test lecture rooms KU Leuven

For this research, an existing university building is modelled. Figure 1 shows the outside and inside view of the test lecture rooms located at the Technology Campus Ghent of KU Leuven in Ghent (Belgium). In this case study, the building contains two large lecture rooms with 140 m^2 floor area and a maximum occupancy of 80 students each. The building is built in 2014 according to the Passive House standard and the design of the building and systems is described by (Breesch et al. 2016).

Figure 1; Left) Outside view of the test building, Right) lecture room used for measurements

Balanced mechanical ventilation is provided with a total airflow supply of 4400 m^3/h for two lecture rooms. Fresh air is supplied by air diffusers (displacement ventilation) in each corner of the room, as indicated in Figure 2. The air handling unit (AHU) regulates the VAV dampers by sending a request signal to control the airflow based on CO_2 concentrations and operative temperature in the lecture room. Each room is a single zone with a supply and return VAV. Set point for CO_2 and indoor temperature (heating) are set at respectively 1000 ppm and 22°C. During weekdays the AHU is switched on at 7:30 and switched off at 17:30h.

Figure 2; Left) Floor plan of the studied lecture room on the first floor, blue is supply air and red extraction air, Right) cross section of the building

For heating purposes, the air is preheated by air-to-air heat recovery, i.e. two cross flow plate heat exchangers connected in series with an efficiency of 78% according to EN 308 (1997). Additionally, a heating coil of 7.9 kW is integrated in the supply ducts of each lecture room. A modular bypass is included.

The building includes an extensive building monitoring system (BMS). A set of sensors has been installed to monitor indoor and outdoor conditions. On the roof of the building a weather station is present that 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 CO_2 concentration and the indoor humidity are continuously monitored. The occupancy of the lecture room is measured by using counting cameras which were installed in the lecture room.

2.2 Monitoring data

For calibrating the simulation model, one minute measurement data for the period of 18-29 of April 2016 is used. The outdoor temperature during the measurement period as shown in Figure 3 was minimum 2°C and maximum 20°C. The outdoor CO_2 concentration, which was not measured, is set at a constant value of 450 ppm. The occupancy profile from 18-22 of April is shown in Figure 3. In this week, the lecture room is used for approximately 30 hours. The maximum number of people present was 50 and a minimum of 12 during the measurement period.

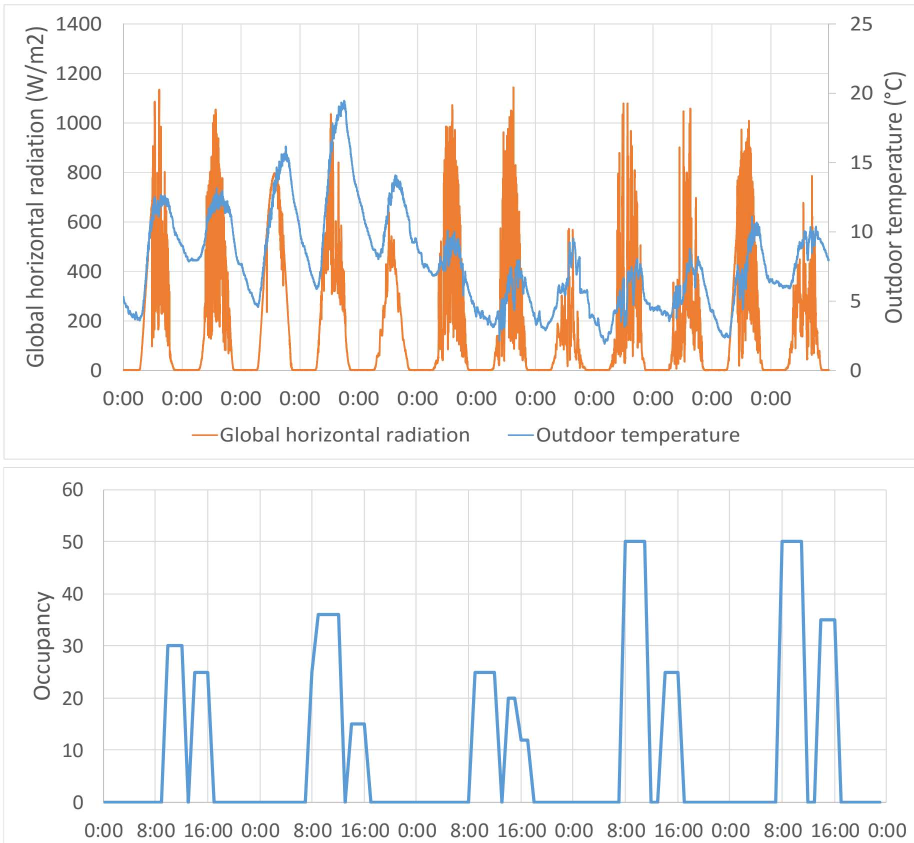

Figure 3; Outdoor weather conditions (above) and occupancy (below) during measurement period 18-29 April 2016

2.3 Simulation model

The simulation model of the case study building is set up in Modelica using the open source libraries of IDEAS and Buildings. The model created with EnergyPlus/ Designbuilder has already been validated see (Merema et al., 2017). The performance of both simulation models is compared to the actual measurement data. The implementation of the control strategy in both Modelica and EnergyPlus will be compared and possible limitations are denoted. Furthermore, the effect of the used control strategy on the energy use of fans and heating coil and the indoor climate is studied. In both models the output time for the results is set to 1 minute. Simulation time in EnergyPlus is set to 1 minute while Modelica is a continuous simulation.

For each part of the simulation model the two approaches used in Modelica and EnergyPlus are presented. Both results obtained in Modelica as EnergyPlus will be compared for the ventilation network, VAV control model, CO2 control model and fan control.

3 RESULTS

3.1 Ventilation network

The ventilation network is the complete ventilation system that connects the outside air to the simulated zone. The network consist of the following components: fans, heat exchanger with bypass, VAVs and ducts. The ventilation loop in Modelica connects the outside air volume with the building zone. Modelica offers the ability to include the pressure drop at nominal air flow rate for the air loop caused by the components present in the loop (e.g. ducts and VAVs). In addition, for the fan the total pressure rise is included at the different air flow rates. In EnergyPlus/Designbuilder the air loop connects the AHU to the VAV integrated in a building zone. In EnergyPlus only the air flow rate is given for the air loop, the pressure drop for the ventilation network is not needed for the input of the simulation.

3.2 VAV control model

In Modelica the damper position of the VAV is controlled by a PI controller, one based on temperature and based on CO_2-concentration. The integration time and the gain factor for the PI control are respectively 120 seconds and 0.1. The actual position of the VAV damper is the maximum output value of the two PI controllers. In addition, a deadband of 1°C on the heating set point of 22°C is included to avoid oscillating of the damper. The reheat coil integrated with the VAV is controlled by the measured room temperature (operative temperature). The supply temperature will be increased to the maximum when the zone temperature is below the heating set point.

In EnergyPlus/Designbuilder, the air flow rate and thus the damper position will change to the maximum air flow when the zone air temperature is below the set point according to the single maximum control logic. This results in a proportional control of the air flow rate, however the integration time or gain factor for the proportional control is fixed. To include a deadband control for the heating set point the Energy Management Script (EMS) within EnergyPlus has to be used to allow the deadband operating. For CO_2 control in EnergyPlus a fixed set point is used. This set point is used by the controller to control the air flow rate proportional to the exceeding percentage of the set point using the EnergyPlus IAQ procedure.

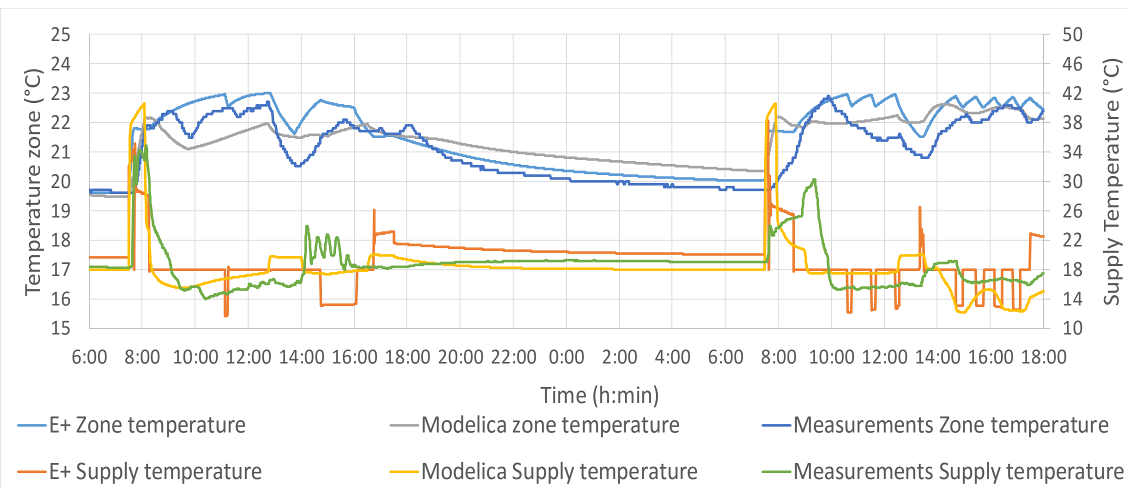

Figure 4; Zone temperature and supply temperature for both Modelica and EnergyPlus

Figure 4 illustrates the zone and supply temperature in both Modelica, EnergyPlus and the measurements for the 18th and 19th of April 2016. For these two days the lecture room is in use from 8:30-12:30 and 13:30-16:30h. During start-up of the AHU it is shown that heating is demanded in the zone since the zone temperature is approximately 19,5°C, resulting in an increase of the supply temperature around 08:00h. Afterwards the supply temperature decreases to approximately 17°C as a result of high internal heat gains from occupants. It is clearly visible that in Modelica the supply temperature is more gradually increasing and decreasing compared to EnergyPlus as a result of the opening times for dampers and valves used for controlling the heating and air flow.

3.3 CO_2 (control) model

To include the CO_2-concentration inside the air model a substance flow source is used linked with an occupancy scheme to simulate the effect of CO_2 production by persons. The CO_2 flow is connected to the fluid inlet of the zone where the CO_2 is mixed with the zone air. At the fluid outlet a CO_2 sensor is connected to monitor the CO_2 values inside the building zone. CO_2 production per person is set at 0,38 l /min. The CO_2-concentration measured at the outlet of the zone is connected to the VAV controller. For the outside air a constant CO2 concentration is assumed of 450 ppm. In EnergyPlus the CO_2 generation by persons is included in the internal gains section by specifying a rate per $m^3/s*W$. The value here is set at $5.77*10^{-8}$ $m^3/s*W$ which corresponds to 0,38 l/min. Furthermore, in both simulation programs the outdoor concentration is set to 450 ppm.

Figure 5 reveals the CO_2-concentrations and air flow inside the zone for EnergyPlus and Modelica. The concentrations are comparable over time, this is affected by the same CO_2 setpoint and the comparable properties for CO_2 generation and outdoor concentration. However, if the related air flow to the CO_2-concentration is compared it is shown that in EnergyPlus 40% less air flow is required to obtain a similar CO_2-concentration as in Modelica. This shows that EnergyPlus underestimates the CO_2-concentration produced by occupants compared to Modelica while the input is the same.

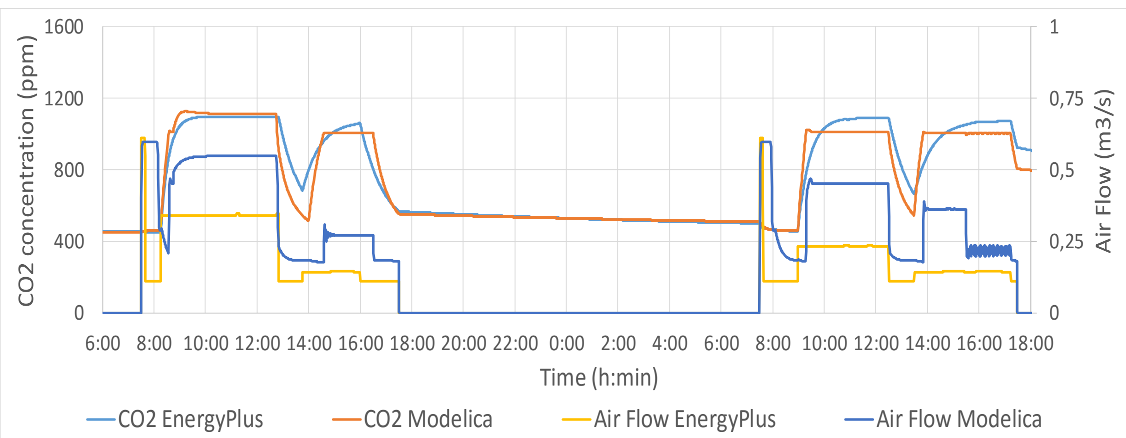

Figure 5; CO_2-concentration in the zone for EnergyPlus and Modelica

3.4 Fan control

Fan control is based on a constant pressure set point inside the duct in Modelica. The constant pressure is influenced by the damper position for the VAV, pressure losses for the complete air loop and the air flow forced through the fan. Furthermore, dynamics of the fan can be included in Modelica. In EnergyPlus the fan is controlled based on the needed outdoor air flow required for the heating demand or to reduce the CO_2-concentration. This results in a good controllable ventilation system with variable air flow rates. For DCV here the maximum and minimum air flow rate are specified. Contrary to Modelica, in EnergyPlus the fans cannot be controlled based on a constant pressure set point inside the ducts. Both programs allow to give a fan power curve in order to calculate the required fan power at the varying airflow rate or to use a fan pressure rise curve in order to calculate the fan power consumption.

3.5 Effect on airflow

Figure 6 depicts the air flow for both EnergyPlus and Modelica. The air flow during startup of the AHU is increased caused by a heating demand in the zone. After the zone temperature setpoint is met the air flow rate decreases to a minimum air flow rate until the CO_2 setpoint is exceeded. The air flow in EnergyPlus is lower during the operation time of the AHU compared to Modelica. EnergyPlus determines the air flow needed in the zone during occupancy based on the product of the number of people and the required outdoor air per person (ASHRAE Standard 62.1, 2007). In addition it is shown that the second and third peak in air flow during both days is earlier in the EnergyPlus simulation compared to Modelica. This is an effect by the method how EnergyPlus determines the required air flow per zone as mentioned before. Furthermore, it is noticed that in Modelica the air flow rate is gradually increasing and decreasing over time while in EnergyPlus the air flow changes in steps according to the time step used.

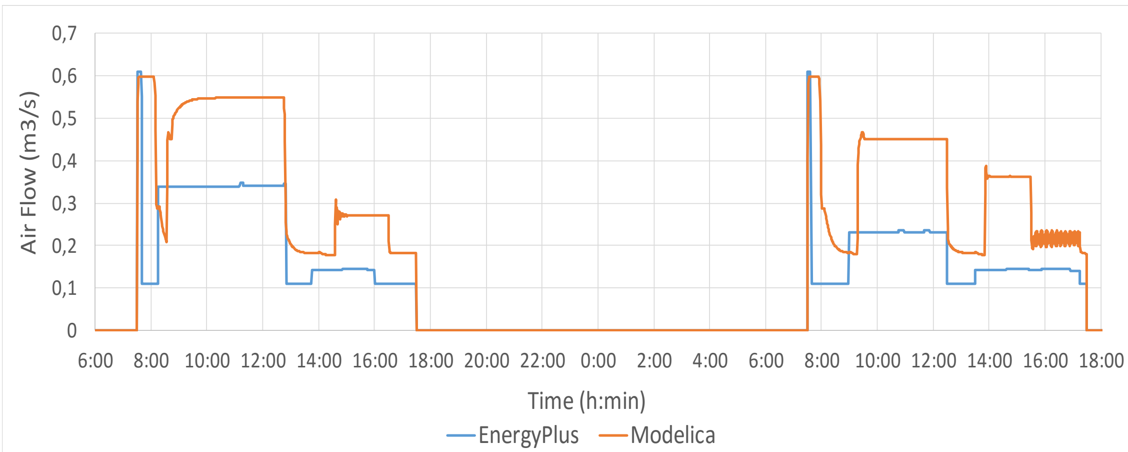

Figure 6; Supply air flow to the zone in both EnergyPlus and Modelica

3.6 Effect on indoor environmental quality

Figure 7, illustrates the room temperature, the supply air temperature, air flow and CO_2-concentration for Modelica, EnergyPlus and the measurement results respectively. The figure indicates that the air flow in Modelica and the actual measurements is gradually increasing/decreasing while in EnergyPlus the air flow changes faster, the change from minimum to maximum airflow occurs over one timestep (one minute) in EnergyPlus.

In general Figure 7 shows that CO_2-concentration can be maintained below the CO_2 setpoint by increasing the airflow rate. For example the CO_2 setpoint of 1000 ppm is exceeded during the first day at 9:00h the air flow rate is increased. Furthermore it is noticed that for the EnergyPlus resuts the air flow is 1250 m^3/h on the first day to maintain a CO_2 of approximately 1000 ppm while for both Modelica and the real measurements the airflow is nearly 2000 m3/h. This indicates that EnergyPlus is underestimating the CO_2-concentration.

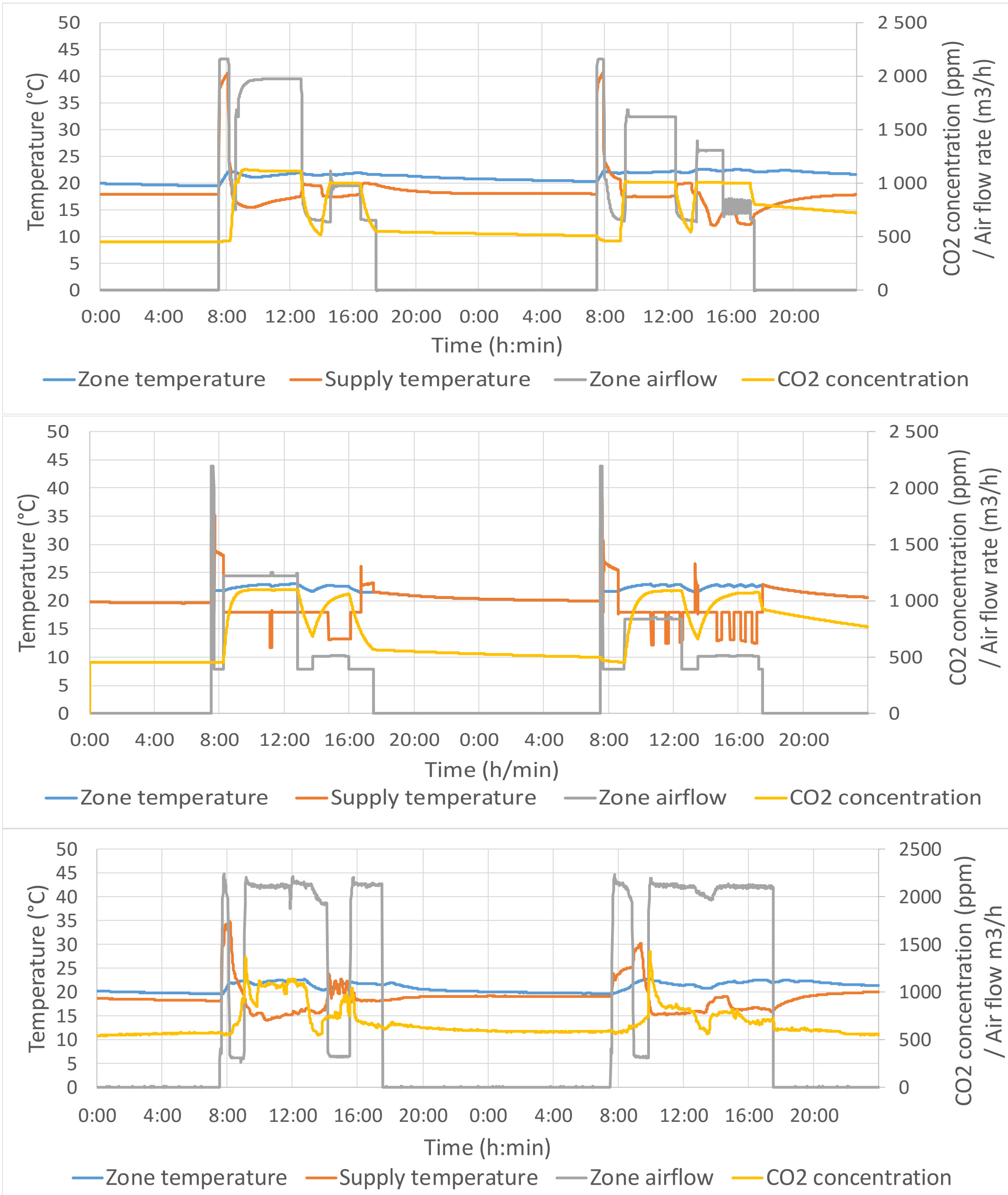

Figure 7; Above) Modelica operation AHU, middle) EnergyPlus operation AHU, below) Measurement data of the lecture room on the 2nd floor from 18 -29 April 2016

3.7 Effect on energy consumption

The annual energy consumption is shown in Figure 8 and is based on simulations in the validated EnergyPlus model. Compared to an CAV system, the savings by implementing DCV are 46% for heating energy and 42% for the fan power consumption during the measurement period. In addition, it is noticed in the measurement results that further optimization of the control can reduce the fan energy consumption even more when observing the CO_2-concentration after the air flow rate is increased. When allowing more proportional control, as in both the simulation results is illustrated in Figure 7, for the air flow rate reductions on heating energy and fan power consumption are respectively 57% and 66%.

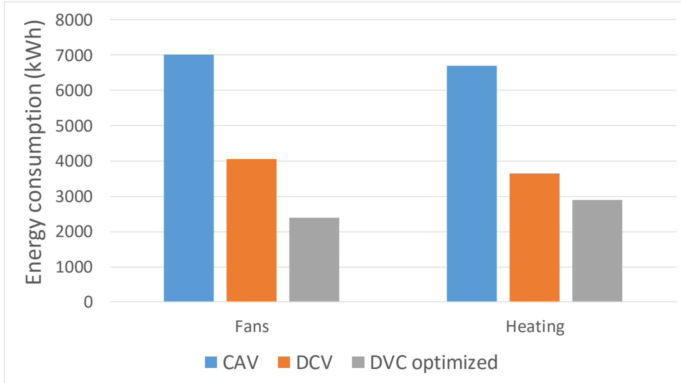

Figure 8; Annual energy consumption based on simulation in EnergyPlus for both CAV and DCV

4 DISCUSSION

Both Modelica and EnergyPlus enable the functionality to implement a smart control strategy for ventilation systems commonly found in commercial buildings. The results show that the IAQ and indoor temperature could be controlled as in the case study building. The energy consumption could be decreased implementing a DCV system that reduced the energy consumption. However, some differences can be noticed between the two simulation environments. It was noticed that CO_2 simulations are underestimated in EnergyPlus compared to Modelica and the measurement results while the same boundary conditions were used.

The study demonstrates that Modelica is able to implement more complex control strategies. In contrast, EnergyPlus does not include detailed control for P, PI and PID control. For example, the airflow in EnergyPlus can be controlled proportional, however the integration time or the gain factor cannot be used as an input. Therefore, the opening time of dampers cannot be controlled. In Modelica the gain factor and the integration time can be set hereby the control strategy can be implemented with more detail compared to EnergyPlus. This enables Modelica to have more control for each specific HVAC component compared to EnergyPlus and to simulate the specific dynamics for each component of the complete HVAC system. In addition, the smallest timestep in EnergyPlus is 1 minute. This limits EnergyPlus to incorporate fast dynamics. Furthermore, detailed pressure modelling for ventilation networks is not included in EnergyPlus. Modelica enables the possibility to simulate the ventilation network more accurately and thus allows more control regarding pressures in ventilation networks.

Designbuilder/EnergyPlus allows to create a detailed geometry of the building using a 3D modeller. For each construction element the corresponding x,y and z coordinate is entered. In Modelica for each construction element only the area or volume is entered combined with the azimuth and the inclination. This means that for windows in Modelica the total area is used while in EnergyPlus every window is modelled at a given position in the wall. This allows EnergyPlus to have more detailed results for the solar heat gains through windows compared to Modelica. Deadband control for the heating setpoint is easier to implement in Modelica compared to EnergyPlus. In Energyplus a fixed heating setpoint is used for the heating coil and an EMS script has to be used to include a deadband. With the more detailed control options available in Modelica the system operation can be simulated in better detail compared to EnergyPlus. For EnergyPlus some good user interfaces are available like Designbuilder and OpenStudio which makes the accessibility of the program easier for new users. However, Modelica made progress in the last few years with the release of easy accessible libraries like IDEAS and Buildings that are well documented. Postprocessing of the results in Modelica has to be done with either Matlab or Python (results are stored in a .mat file) while for EnergyPlus some good result viewers can be used.

5 CONCLUSION

With the future requirements for building energy consumption, the effect of control of HVAC systems on the energy consumption is increasing. In order to simulate these effects the BES tool needs to include the dynamics for these components. Since the impact of control in nZEB buildings on the total energy consumption is more significant. Modelica is a useful simulation tool to include a more complex control for HVAC systems compared to EnergyPlus. With the recent developments in Modelica and the availability of open source libraries, BES models can be easily constructed. Furthermore, since Modelica is an open source structure new components can be implemented in an easy way and can be exchanged by the users. However, EnergyPlus is still a useful and powerful and accurate BES software to calculate energy consumptions in an early design phase. Models can be quickly created using Designbuilder and results for energy predictions are accurate.

6 ACKNOWLEDGEMENTS

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