Evaluation and optimization of the performance of the heating system in a nZEB educational building by monitoring and simulation

Authors:

1. Martina Borrelli, PhD student
   University of Bergamo,
   Department of Engineering,
   via Marconi 5,
   24044 Dalmine, BG, Italy,
   e-mail: martina.borrelli1@unibg.it

2. Bart Merema, PhD student
   KU Leuven
   Department of Civil Engineering
   Buiding Physics and Sustainable Buildings, Ghent and Aalst Technology Campuses,
   Gebroeders De Smetstraat 1
   9000 Gent – Belgium
   e-mail: bart.merema@kuleuven.be

3. Fabrizio Ascione, Associate Professor
   University of Naples
   DII - Department of Industrial Engineering
   Piazzale Tecchio, 80
   80125 Napoli – Italy
   e-mail: fabrizio.ascione@unina.it

4. Rosa Francesca De Masi, Assistant Professor (*corresponding author*)
   University of Sannio
   DING - Department of Engineering
   Piazza Roma, 21
   82100 Benevento – Italy
   e-mail: rfdemasi@unisannio.it

5. Giuseppe Peter Vanoli, Full Professor
   University of Molise
   Department of Medicine and Health Sciences -Vincenzo Tiberio
   via G. Paolo II contrada “Tappino”
   86100 Campobasso – Italy
   e-mail: giuseppe.vanoli@unimol.it

6. Hilde Breesch, Assistant professor
   KU Leuven
   Department of Civil Engineering
   Buiding Physics and Sustainable Buildings, Ghent and Aalst Technology Campuses,
   Gebroeders De Smetstraat 1
   9000 Gent – Belgium
   e-mail: hilde.breesch@kuleuven.be

Abstract

The optimal control of the HVAC system in the nearly zero energy buildings (nZEBs) can be considered as a challenge. Indeed, the lack of data given by monitored data does not allow understanding what are the implications of different strategies on thermal comfort and energy consumptions. This paper determines an approach for the evaluation of the management of the heating system in an existing educational nZEB. The aim is to understand how the energy efficiency of the heating system is sensitive to controls strategies and the important role played by the control systems. The test lecture rooms on KU Leuven Ghent Technology Campus (Belgium) have been chosen as case study.

A deep analysis, starting from an in-field monitoring, was carried out during the winter period of 2019, in order to assess the actual operation and the energy use of building systems under real conditions. Then, a building energy simulation (BES) model of the building and its systems was developed and calibrated against the real monitoring data. Control strategies of the heating system are simulated and compared to the current configuration. The simulation results show that strategies based on a definition of a heating curve for the boiler can reduce the comfortable time (-23%). Controlling the temperature inside the storage tank as a function of the outdoor temperature together with the control on the activation of the air handling unit result in an energy savings from 32% to 46%, with a correspondent increase of comfort time in the period from 0.6% to 3.4% compared to the baseline scenario, depending to the relationship between the external temperature and water temperature inside the water storage tank.

Keywords

Nearly Zero-Energy Buildings (nZEB), School building, Measurements, Buildings performance, Energy saving, Building energy simulation, Improved control strategies.

1. Introduction and literature State of the Art

The last recast of the Energy Performance of Building Directive (EPBD 2018/844/EU) [1] committed the EU Member States to develop "a sustainable, competitive, secure and decarbonised energy system" by 2050. These ambitious long-term international targets cannot be achieved without a strong reduction of energy demand in the building sector. It is, still today, one of the most important contributors to the global energy balance (with a global share between 35 and 40% in developed countries) and related greenhouse gases' emission. In this perspective, the EPBD recast [2], already in 2010, established that all new buildings have to be Nearly Zero Energy Buildings (nZEB) starting from the beginning of 2021, with an anticipation of two years for buildings owned or occupied by the public Institutions. Often, even if net and nearly-zero energy buildings are designed to be energy efficient, the energy performance predicted in the design phase could not match the measured performances; this common phenomenon is the so-called "performance gap" [3].

At the European level, in non-domestic buildings, the energy consumption of the HVAC system is the main end energy use, with a weight close to 50% of the overall energy demand [5]. Hence, it is clear the importance to optimize the operation of buildings and HVAC systems, that result very sensitive to control strategies and management and to a different level and consciousness of user interactions. For instance, in this regard, Gunay *et al*. [4], by examining the operational parameters of the HVAC that impacts on the performance gap in office buildings, have shown that habits of the occupants and default features of equipment could be improved for bettering the system operation. They also found that the start and stop times of the Air Handling Unit (AHU) and the ventilation rate are the most critical parameters that

affect energy and comfort performance in buildings. More in deep, one-hour change in AHU start or stop time is estimated to affect the HVAC energy performance by about 4% for the investigated buildings. Really, the topic of the role of occupant behavior is very actual, having a great impact on buildings' energy demands.

With reference to non-residential buildings, the time-dependent nature of their heating loads gives the possibility, by studying the heating load variation, of improving the efficiency of energy systems and to reduce the energy consumption and system operating costs. Ding *et al*. [6] proposed a multi-objective optimization algorithm, by showing that, without compromising the requirements of the thermal comfort of building occupants, the energy system operating cost can be reduced of about 40%, with an increase of system coefficient of performance compared to the current experience-based operation strategies.

Often, the availability of real monitored data is limited, because few studies in the matter of in-field monitoring campaigns and about operational behavior and energy performance of building in a "real use" condition are available, at today. Really, the knowledge-transfer and the exchange of experiences resulting from pilot programs are crucial to avoid the mismatch and to spread strategies of management, design logic and information about the operational energy performance of systems and equipment for the indoor microclimatic control, given the high energy demands needed for satisfying such building service. Furthermore, the knowledge of how the energy is used and the real boundary conditions could help to improve both the reliability and usefulness of building simulation models, that can be then used for enhancing the construction of new ones [7]. The study of energy demands, in a real operational context, might support the improvement of the energy performance of existing buildings, the behavior change [8] and can support energy efficiency policies. Starting from monitored real data, it is in general fundamental to detect malfunctions, to improve the control of the systems and to optimize the overall building performance, energy use and indoor comfort conditions. In this regard, Carlon et al. [9] started from a one-year monitoring campaign of a building and evidenced the importance of a better management of the thermal inertia of the heating system; then, these authors tested improved control strategies by means of suitable simulations.

The optimization of HVAC control in high efficient buildings, is worth investigating. The most recent paper of Bechtelet al. [10] have shown that in single family houses, a model predictive controller determines the cost-optimal operating cycles of the heat pump in combination with thermal energy storage. Liu et al. [11] have evaluated as control strategies of a heating and cooling system: adjustment of set-points for heating and cooling and adjustment of set-points together with a rule-based weather predictive control strategy. The paper of Guillen-Lambea et al. [12] is focused on the control strategies for the energy recovery ventilators. The optimum strategy during winter is a control based only on the sensible energy. The optimal strategy found for the summer season is based on the enthalpy control. Georgiou et al. [13] have introduced a novel approach able to adapt to a given PV generation and load demand and individually control the battery and the net grid energy. Aranguren et al. [14], by means of a numerical model, have proposed the adoption of a thermoelectric cooler-heat pump. Taking into consideration the lowered heating and cooling load of high efficient buildings, the adoption of a natural heat transfer air-conditioning terminal device has been investigated by Shu et al. [15]. Finally, Huang et al. [16] have underlined another important aspect: a proper control of the nZEB cluster is essential for improving load matching, reducing grid interaction and reducing energy bills.

Briefly, most of the recent papers about the nearly zero energy building are focused on the optimization of solution design, on the global energy balance or thermal comfort. Few papers give suggestions on the management approach for optimizing the activation of HVAC system and there is a poorness of experimental data for validating the operation in real conditions.

More in general, without considering the case of nZEB, in the available scientific literature, the most investigated HVAC control strategies are based on the model predictive control (a very up-to-date frontier) or these are rule-based strategies. In particular, the first logic is implemented with the aim to improve the real-time management of storage tanks [17], boilers [18], district heating systems [19-20]. For instance, in [21], with reference to the heating and cooling systems of office buildings, the model predictive control is applied to improve the indoor microclimate control. On the other hand, with reference to the rule-based and association rules, there are a number of control strategies, like the occupancy-based heating control proposed by Shin et al. [22] for the optimal start and stop control of radiant heating systems to improve the energy saving and the thermal comfort. There are control strategies based on weather compensation, for which the supply water temperature is related to the outside air temperature according to specific heating curves [23] or mathematical correlations. In this matter, Péan et al. [24], in a huge review about existing controls aimed at improving the energy flexibility of building systems, have provided a clear difference in terms of concept and complexity of predictive and rule-based controls. A self-tuned HVAC controller that provides customized thermal conditions to satisfy occupant preferences while minimizing energy consumption, and its implementation in a real occupied office has been proposed by Lee [25]. Most advanced strategies are also proposed basing on simulation tools. For instance, Shunian et al. [26] have proposed a stochastic optimized chiller operation strategy based on multi-objective optimization and measurement uncertainty. Gue tel al. [27] by employing four wise metaheuristic algorithms, have studied a control for residential buildings through predicting heating and cooling loads. Ganesh et al. [28] have solved an optimization problem for calculating the ventilation rate that minimizes the total energy consumption, while maintaining the indoor pollutant concentrations below to acceptable thresholds. The proposed techniques are really innovative but the effectiveness on the management of real HVAC has not been proven.

Here, the aim of this study is to investigate the actual operation and energy use of an existing nZEB educational building, as the starting point to identify alternative control strategies for the heating system and then to demonstrate how the overall performance could be improved by managing differently the same installed equipment. A method, based on monitored data, is introduced for identifying the optimal management of the heating system. The novelty of this study, under both the point of views of methods and application, is the improvement of an existing educational nZEB, by evidencing that energy demand can be reduced and also indoor thermal comfort conditions can be improved, at the same time. One of the main findings is that, as also sustained in [29], buildings designed to be high energy efficient require a deeper investigation of the management of air conditioning systems compared to a traditional building. A building designed to have a high passive control of internal conditions could allow the use of control strategies and optimized managements able to further decrease the energy consumption, still maintaining indoor comfort conditions for the occupants. Indeed, usually the management of air conditioning systems are based on a “fixed point” by the use of a constant setpoint temperature in each room or in the most representative ones. Moreover, sometimes thermal storages are maintained at a constant temperature to avoid the effect of time lag (due to the inertia) at the start up. Furthermore, the supply temperature, of water or air, often is chosen based on conventional values, without considering that it could cause an overheating effect, during the heating season, compared to the optimal comfort conditions, with further negative effects, and thus the increase of thermal losses and of the energy demands for the heating service. In this vein, the present study want prove how the energy efficiency of a nZEB is sensitive to controls strategies and the important role played by the control systems: really, the control strategy is fundamental to ensure that the building operates as efficiently as possible, in terms of energy demands and thermal comfort.

This study is performed using an existing case study: the test lecture rooms of the KU Leuven Ghent Technology Campus - Belgium. Starting from the current HVAC system configuration, and thus by monitoring data then implemented

in a validated numerical model, different control strategies are proposed and tested, all based on heating curves for the control of water supply temperature and the water storage tank temperatures dependent from the outdoor one, on the shifting back of AHU's switching on, and also by proposing the introduction of a set-back value for the water temperature inside the storage tank. The investigated control strategies will be described in the simulation set up section, then these will be tested in a simulation environment based on the Modelica open language [30], and the results are then compared to the baseline scenario and each other, in terms of both achievable thermal comfort and required primary energy demands for the space heating service.

2. Case study description

The case study is an educational nZEB on the Ghent Technology Campus of the KU Leuven in Ghent (Belgium). The city, characterized by a temperate climate, is located in the East-Flanders of Belgium, in a climatic zone Cfb according to the Köppen-Geiger classification [31]. The main climate statistics [32] are provided in Figure 1.

Here Figure 1

The building has been designed with the aim of fulfilling the passive house standard, and with the purpose to have a school building that, at same time, can be used as lecture rooms and as a test facility for scientific research in the matter of building energy-efficiency, in a "real use" operation [33].

The building was realized on the top of an existing university edifice and it contains two lecture rooms (1-2) with a floor area of 140 m^2 and a heated volume of 380 m^3 each, a staircase (3) and a technical room (4). The whole construction is shown in Figure 2. A detailed description of the design choices is reported in a previous paper of some authors [33]. Some details are proposed for improving the readability of the paper. The lecture room of the first floor has a brick external wall (14 cm) with exterior insulation (19.3 cm) with wood frame paper flakes insulation and wood fiber; on the internal side there are timber frame (4.0 cm) and fiber cement panels (0.8 cm). The upper classroom has a lightweight timber frame external wall (4.0 cm) coupled with fiber cement panels (0.8 cm) and the same insulation of the lower floor with oriented strand board and 1.0 cm of plasterboard on the inner side. These have the same thermal transmittance value (U) equals to 0.15 W/m²K. Both lecture rooms have a concrete slab floor.

The window-to-wall ratio is 26.5% on both facades and the window-to-floor ratio is 13%. The windows have triple glazing with g-value of 0.52 and these are equipped with internal and external solar shadings. The windows offer both the possibility of manual and automatic operability. Moreover, also the external shading systems, on the southwest façade, can be both automatically and manually activated.

Here Figure 2

The heating and cooling needs are satisfied by means of an all-air system, with a balanced mechanical ventilation, with a total supply airflow of 4400m^3/h. Each classroom is a single zone, with a supply and return VAV (i.e., Variable Air Volume) boxes regulated by the AHU, by means of a request signal to control the airflow, based on CO_2 concentration and operative temperature inside the classrooms. Thus, it is an application of Demand Control Ventilation. For the space cooling needs, when necessary, the AHU cools the supply air by controlling the modular bypass of the heat recovery section and by using an indirect evaporative cooling (IEC). Conversely, for satisfying the space heating needs, the primary air is both preheated by an air-to-air heat recovery with modular bypass and, after, the active heating is achieved by the

passing through a water heating coil of 7.9 kW, integrated in the supply ducts of each classroom. The heating generator is a condensing wood pellet boiler, with a nominal thermal capability of 7.8 kW, equipped with an internal water storage tank with a volume of 0.6 m^3.

During the winter season, the setpoint levels for CO_2 and indoor temperature are settled at 1000 ppm and 22°C respectively, while during the night the HVAC system operates in standby mode, with the heating set back decreased to 15°C. The lecture rooms, with a maximum occupancy of 80 persons, are usually used from Monday to Friday, between 8:15 and 18:00. In general, the academic year counts 124 days of activity, with university courses (September-December and February-May) and 63 days of exams (in January, June and August-September). The value of set point has been indicated by the building users. Indeed, they have specified that when the set point was fixed to 20°C, occupants have declared discomfort conditions inside the lecture rooms (temperature in the rooms quite cold).

Finally, with reference to the systems and equipment for the managing and monitoring, the building is fully monitored through a set of sensors installed in order to collect all variables necessary to characterize the indoor and outdoor conditions. Moreover, the building is provided with a dedicated weather station that monitors the main outdoor parameters, and thus solar radiation, outdoor temperature, humidity, wind speed and direction. For what concerns the indoor conditions, the air temperature, relative humidity, and CO_2 concentrations are continuously monitored with a time step of 1 minute, while the occupancy level is measured by a motion sensor and a high definition camera, with face recognition. The operation of the HVAC system is fully monitored too, by means temperature and mass flow sensors located inside the main sections of the system. All these recorded data are collected in an accessible database, so that these are available for further elaborations.

3. Methodological approach

The methodological approach of the present work consists in two parts: the experimental one, described in the sub-section section (3.1) and the simulation one (3.2).

3.1 In field monitoring

The starting period of the winter academic season 2019-2020 has been chosen for the campaign, and thus from the beginning of October until the end of December 2019. During the monitoring phase, the two test lecture rooms were occupied by the students of the university courses, and thus this allowed the evaluations of the actual operation and energy use of the building and facility, under a real condition of use. More in detail, the results are shown for the month of November 2019. Environmental, thermal, energy and configuration parameters are shown as: a) air temperature (zone and supply), b) VAV damper position (in order to evaluate the actual supply airflow), c) the CO_2 concentration in rooms, d) the outdoor conditions from the weather station, e) the supply water temperature and f) the water mass flow from the boiler, g) the thermal power at the AHU heating coils. Moreover, further variables, and thus doors and windows opening, occupancy level and HVAC operation time, have been used to evaluate the reliability of achieved results.

Properties of the main sensors used for the measurements are listed in Table 1. The time interval used for the measurements is 1 minute.

Here Table 1

The monitoring data have been used both to assess the actual operation and energy use of the case study building and to understand the possibility to have a better management of the hot water supply, by identifying some possible alternative control strategies, that will be described in the simulation set-up section.

3.2 Numerical Modeling and Simulation

The simulation analysis is carried out to demonstrate how the overall performance of the heating system could be improved, by using a better control strategy and then how improving the choice for the management of energy systems in existing buildings can affect their energy consumption and the indoor comfort conditions for the occupants.

Dynamic building simulation is an essential tool for the designing of appropriate system solutions and to test different control strategies in existing buildings too. In this study, the dynamic simulation environment Dymola and the equation-based Modelica [30] language were chosen for the modeling of the complex systems, and thus building and equipment. Modelica is an object-oriented equation-based language; it is a continuous-time system simulation tool that operates diversely from the widely used programs that calculate solutions at discrete time intervals. During the last years, various kinds of open source libraries have been developed, for including building components like envelope and HVAC systems, as well as detailed controls systems.

Obviously, the dynamic simulation model of an existing building must be correctly settled-up and calibrated, to ensure that the model is representative of the real behavior of the building under analysis. There are several standards to follow for the correct calibration of the models, through codified procedures and protocols and, in this study, the model validation has been performed by taking into account the ASHRAE Guideline 14 (2014) [34], based on detailed monitoring data of building and HVAC systems.

The validation process of a building model is an iterative process of comparison among the outputs of a simulation and those derived from measured data, by determining the deviation of the results and the degree of uncertainty. This process starts from the setup of the numerical model, created as accurately as possible, by assigning all the information about geometry, thermal properties of the constructions, real weather data, properties and control logic of the HVAC and electrical systems of the building and by setting activity and schedules for equipment and occupation. Then, starting from the baseline model created and whose outcomes are deeply analyzed and compared to the monitored data, a trial and error approach is adopted to manually adapt the variables which results not have a satisfactory correspondence among the simulated outcomes and the real measured data. This is the “calibration phase”, in which input data, boundary conditions and possible modelling errors are corrected. The goal is to achieve a numerical model that properly represents and reproduces the real base scenario, so that it can be expected that design alternatives implemented in the model can offer reliable results for what concerns their application in the real facility. Finally, the availability of a validated and calibrated numerical model of a real building energy performance is a powerful tool for designing design alternatives and understanding their feasibility, in terms of technical, economic, environmental usefulness.

The most diffused and adopted approach for the energy modeling calibration is described in the ASHRAE Guideline 14. According to this approach the statistical indices adopted in this paper are: the Mean Bias Error (MBE), given in equation 1, and the Coefficient of Variation of Root Mean Square Error (CvRMSE) as shown in equations 2-4.

$$MBE = \frac{\sum_p (S - M)_{daily}}{\sum_p M_{daily}} \quad (1)$$

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

$$A_{hourly} = \frac{\sum_p M_{interval}}{N_{interval}} \quad (3)$$

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

In the equations above reported, S is simulated data, M is measured data and N is the number of sampling. Obviously, lower is the value of these indicators, better is the quality and the predictive capacity of the numerical model. In particular, the ASHRAE Guidelines requires for the MBE a value ≤ 10% and for the CvRMSE ≤ 30%, when the validation is performed on the basis of hourly data; for monthly data, the requirements are respectively ≤ 5% and ≤ 10%. Since for daily data there is not a requirement specified by the Guidelines, the same requirements as for the hourly data have been used in this research. Surely, this is a conservative approach. It should be noted that both indices (MBE and CvRMSE) have to be calculated, indeed the first one offers the mean gap and the second one provides information about compensation errors.

The calibration procedure requires some iterative actions to find the better approximation of the real building. If the adopted calibration indexes are not convergent, it is necessary to evaluate the limitation of the model and find a direction to modify the input data. With reference to the case study model, the main criticalities and limitation in the input process have been avoided. First of all, the numerical simulation needs of a weather file as input. It is defined with outdoor data monitored by the weather station on the building, at the same time and with the same time step with which the energy consumptions are monitored. This procedure allows the evaluation of the calibration indexes for reliable internal and external forcing. Another important aspect is the description of the building envelope and HVAC system. In this paper the design values have been used and this can be considered a limits of the baseline model. Indeed, the value of thermal transmittance as well as the value of efficiency of plant sub-systems have been not verified by means of measures. However, the design information seemed sufficiently accurate and updated for describing the model. The thermal zones have been described according to the real use and occupation patterns both for people activity and for their interaction with regulation system or with windows opening.

However, it has to be underlined that there will be a difference between the simulated and measured values of indoor parameters also due to the thermal stratification inside the zone that is due to the natural convection (the all air heating system, obviously, has convective terminals) and this spatial effect is not implemented in Modelica. Indeed, in order to have a suitable analysis also in the domain of the space, besides that time-variable, the coupling of BPS (Building Performance Simulation) and CFD (Computational Fluid Dynamic) is necessary. This can be considered as a limit of the proposed model that may be investigated in future research.

The calibration process will be described in section 5.2. Then, the alternative control strategies have been implemented in the calibrated numerical model of the building in order to have different scenarios to test, and the results are compared to the baseline model and each other, in terms of primary energy consumption and comfort condition inside one of the two lecture rooms during the time of students' occupation.

4. Operation of the HVAC system based on monitoring data

In this section, the HVAC system response to the heating and hot water demand is experimentally investigated. Furthermore, the real operation of the AHU and of the combustion pellet boiler in the considered system configuration are characterized, in order to implement this operational peculiarity into a suitable energy simulation model.

According to the monitored data, the pellet boiler is always available to provide hot water for the space heating needs of both rooms, separately. The AHU is turned on from 7:30 a.m. to 6:00 p.m. and, according to the heating needs, the AHU sends a request signal to the supply pump of the hot water supply.

In Figure 3, for the classrooms E120 (first floor) and E220 (upper floor), the supply airflow rate, the room temperature and CO_2 concentration are shown, with reference to the whole November 2019. During the AHU operation hours, the airflow in the classrooms increases as result of the low room temperature and high CO_2 concentration. During the start-up of the AHU, as a result of a low room temperature in the morning, the supply airflow increases, by exceeding 2000m^3/h, in order to allow the temperature setpoint inside the rooms. Conversely, when the zone temperature exceeds the setpoint, the airflow decreases. Moreover, it can be seen that, after the end of a lecture, the system still operates at a certain airflow rate, in order to reduce the CO_2 concentration in the rooms. Moreover, during the low or no occupancy periods, the airflow decreases to a minimum, in order to reduce the energy demands for fans. In general, the air system works as it is designed and according to the expectations, on the base of the planned scheme of demand control ventilation.

Here Figure 3

In Figure 4, the supply water temperature from the boiler, the air temperature at the AHU's heating coil, the temperature inside the rooms and the indication (with grey areas) of the time during which the system requests hot water from the boiler are provided, still with reference to the month of November 2019. The results show that, during the AHU start-up, the boiler immediately provides water at a temperature also above 60°C, in order to heat the supply air which temperature increases from 16°C up to 30°C to meet the heating setpoint in the classrooms. Indeed, even if slowly, also the temperature inside the rooms increases, by reaching the setpoint temperature after about one hour from the AHU's start-up.

Here Figure 4

Finally, in Figure 5, the daily energy demands for the fans and the thermal energy provided from the boiler to the AHU's heating coils, with reference to both the classrooms, are reported. Furthermore, here it is also reported the indication, for each day of the month, of the parameters that affect the energy demands, and thus the operating hours of the pump for the water supply for each room, the mean outside temperature, the daily occupancy inside the rooms (in terms of the mean number of people and number of hours of occupancy) and the supply water temperature at the heating coils.

Here Figure 5

Figure 5 suggests that the AHU consumption changes according to the occupancy. On 11th November, for instance, there are no people inside the lecture rooms, and thus a high energy request is recorded, with reference to both fans and thermal need, because the system works to meet the setpoint temperature without the thermal contribution due to the

occupancy (i.e., the heat endogenous gain). Surely, the occupancy is an internal load that positively affects the overall heating load, by reducing the thermal energy need, but, on the other side (in this configuration of HVAC system) also increases the ventilation requested to reduce the CO_2 concentration inside the lecture rooms. As shown, during the last three days of the month, the mean outdoor temperature progressively decreases and the fans energy consumption increases. Moreover, the thermal energy needs are clearly affected by occupancy and outdoor temperature, in both cases with an opposite correlation (i.e., the heat demand rises when occupancy and/or outdoor temperature decrease). More in deep, the occupation hours are comparable, but on 28th there is the highest thermal need with an intermediate outdoor temperature and a lower occupancy inside the rooms, while, on 29th, there is the lowest thermal need despite the lower outdoor temperature. During the 27th November, the outdoor temperature is the highest, but the thermal demand is intermediate, giving that the occupancy is lower compared to the 29th November.

The monthly lowest outdoor temperature is measured during the 21st November (of course, with reference to this month), when the energy consumption is relatively high but not the maximum value of the month because of the positive occupancy effect. Indeed, a high energy consumption occurs during the 11th and 18th of November. In particular, for the first day, the thermal need is high, because there aren't people inside the lecture rooms and thus there is a lack of the positive contribution of the internal load to meet the setpoint temperature. Diversely, during the 18th November, the higher energy consumption is due to the opening of the door of the room E220. In general, the lower thermal demands are recorded for the room E120, that is the most used, in terms of time and mean number of occupants.

As expected, there is a relation between the supply water temperature and the internal needs. This temperature is higher when the outside temperature is lower and, moreover, this is affected also by the occupancy rate, as above already justified.

In general, the monitoring results show how the system suitable response to the outdoor and indoor conditions and optimizes the behavior to minimize the energy demands and to meet comfort conditions inside the building. On the other side, there is a possibility of improving the management of hot water generation and storage: indeed, according to the current control logic, the pellet boiler keeps the hot water inside the integrated tank at a quite high and constant value of temperature, over the time, without considering the time-varying nature of the heating loads of a university building. In the next section, the possibility of improvements is investigated.

5. Set up of the building and HVAC system model

In the following sections, firstly it will be shown the model creation and validation process, and then the alternative control strategies are proposed and described.

5.1. Building simulation model

A previous simulation model of the building was created in Modelica (Dymola, 2018) and calibrated according to the ASHRAE Guideline 14 (2002) [34]. A detailed description of this model and related calibration against real measurements is inferred in a previous work [35]. In additions, according to the purposes of the present study, the model has been updated, by using a new version of the same tool (i.e., Dymola 2020) in order to implement the hot water generation section in detail (i.e., the pellet boiler, the tank and the water pumps with related controls). In particular, the added components are derived from the *Building* open-source library [36] and are reported in Table 2. These sub-modules have been used to simulate specific components related according to the mathematical model implemented in Modelica. All components have been connected in order to create the complete a model of the case study building as shown in Figure 6.

Here Table 2

Here Figure 6

All the parameters of existing models have been properly settled to model as accurately as possible the real components behavior. The main assumptions and modifications are summarized here. First of all, the water tubes have been modeled as a fixed resistance with a pressure drop of 200Pa (by *IDEAS.Fluid.FixedResistances.PressureDrop*). Concerned the heat transfer between boiler-tank and external environment where the boiler is located, a value of thermal conductivity equal to 0.035W/m^{2}K has been settled and a fix value of air temperature equal to 10°C has been chosen as boundary condition.

Modelica allows the definition of a detailed control for the HVAC system, by means of the task *Buildings.Controls.Continuous.LimPID*. In particular, the hot water generation from the boiler is controlled by a proportional control with a gain factor of 0.7. The thermal generation from the pellet boiler keeps the water temperature inside the tank at 60 - 65°C. Furthermore, two PI controls have been used to manage the hot water supply from the water storage tank to the AHU heating coil. In particular, the chosen gain factors are 0.01 for the PI pump control and 0.08 for the three-way valve control, with an integration time of 180s in both cases. The control logic is conceived for obtaining the setpoint temperature inside the room, measured by a temperature sensor with radiative fraction settled to 0.15. In addition, a dead band equal to 1 °C on the heating setpoint of 22°C is included in order to avoid the oscillating of the damper in the air section of the system.

Regarding the water loop, the following boundary conditions are set: pressure drop of 3bar and water temperature of 10°C (by *Buildings.Fluid.Sources.FixedBoundary*). Moreover, the outside temperature is constantly measured by the weather station and used as input for the HVAC system control by means of the following tasks: *IDEAS.BoundaryConditions.SimInfoManager* and *IDEAS.BoundaryConditions.WeatherData.ReaderTMY3*. As input air temperature for the ventilation system, the outside temperature measured inside the AHU is used. Finally, with reference to the shading devices, artificial lighting and occupancy, the measured data from the building monitoring system (BMS) have been included inside the simulation model, with reference to each day of the simulation period, by using detailed schedules. More in detail, the adopted internal heat gains are: 1100 W/room with convection/radiation fraction of 50/50 for the lighting; 73W/person and convection/radiation fraction of 60/40 for the occupants modelling.

5.2 Model calibration process

To calibrate the model, the monitored data (i.e., the one-minute time interval registrations) available from the BMS are used, and the calibration indices were calculated on daily basis.

The simulation results are calibrated with reference to the heating demand. Really, in order to verify, in the main section of the system, if the model behaved like the real system, also the following variables are analyzed and checked during the validation process: air temperature and CO_2 concentration inside the room, operation of the ventilation system (in terms of temperature and mass flow of air streams), operation of water circuit (i.e., temperatures and mass flow of supply and return water from the boiler storage tank) and the thermal power of the heating coil. In detail, to evaluate if the results of these variables were comparable with the measurement results, with reference to each validation steps, the simulation outputs are compared with the measured trends and the calibration indices MBE and CvRMSE have been evaluated. The resulted indices, at the last step of the calibration process, are shown in the Table 3. These indices indicate

that there is a good agreement between the simulation model and the monitored results for all the considered parameters. This is an important result, because when data with a short time step (minute, hour, day) are compared, it is really difficult to reach the calibration convergence. Indeed, due to the simplification explained in section 3.2 and to the implicit limits of the calculations tool, also when the global parameters (monthly or annually based) are comparable, the behavior, at short time step, could be very different. Indeed, a compensation of errors could bring to satisfy results. About it, it is really interesting to analyse the comparison between the measured and calculated heating power. Figure 7 shows the comparison for a test period of two-weeks. At daily level, the indices proposed in table 3, indicate that the threshold values are respected. However, the analysis of this figure indicates that, when the comparison is done with short time step (minutes in this case) a large difference between the two values is noticed on for instance November 15th. For a few minutes the monitored demand is double the simulated one. This can be explained by a peak absorption during the on / off cycle, or by some instabilities of the battery power supply network, or by a transient water flow. These phenomena are not controllable by the simulation program and cannot be replicated. However, the overall performance and the trend of heating power is comparable.

Here Table 3

Here Figure 7

Moreover, it has to be taken into account that in order to calibrate the model, the following parameters were adjusted during the calibration process: the parameters of pump and three-way valve PI controls, the value of air tightness and the boundary temperature used by the model in order to evaluate the heat exchange between the lecture room and the other thermal zones not included into the building model.

Regarding the PI control parameters, by supposing some common values for the gain factor and the integration time, these were ranged until obtaining the same behavior of the real components. In other words, they were adjusted until the simulated trends and values of the supply and return water temperatures, mass flow and power exchanged in the heating coil, resulted comparable to the measured values. Meanwhile, some adjusted actions were also taken about air tightness. In particular, starting from the values obtained from a blower door test, performed a few months before, and considering that during the validation period the windows are not locked, the starting valued was increased until obtaining the minimum value of the validation indices and then the best agreement between the predictive capacity of the model and the actual behavior of the real system.

As a final step, in order to evaluate if the results of the room temperature are in agreement with the measured values, it has been verified if the simulation results are within the magnitude of ±0.5°C compared to the measurements.

Figure 8 proposes the comparison of the measured and simulated values and the calculation of the difference. First of all, it is clear that the trends are comparable and it is confirmed by the Mean Bias Error proposed in table 3 (0.31%). This index, calculated basing on daily valued, is not a measure of the model error. It is primarily used to estimate the average bias in the model and to decide if any steps need to be taken to correct the model bias. By observing the trends in figure 8 that are based on data per minute, it is clear that the simulated values have lower peak values compared with the measures but these are still within the limits of ± 0.5 °C. This difference is higher during the night and the weekend (i.e. 16th and 17th November). This difference can be mainly attributed to different inertial behavior of the building-HVAC system and partially to the modelling of the occupant and equipment gains. Indeed, the indoor temperature depends from internal and external forcing as well as from the answer of the building envelope when the HVAC is turned off (night and weekend). The building envelope contributes to attenuate and phase out over time the heat according to its thermal inertia.

The simulation model is not able to perfectly reproduce this behavior and during the night there is a difference of more than 1.0°C. This phenomenon is evident especially during the weekend, where the temperature in the room is even 2°C less compared to the measured value and this also reflects in a different reaching of the temperature in the following morning. Indeed, considering the night between 17th and 18th November, it is clear that, without occupants and HVAC, the model of the building envelope can approximate the real behavior with limited uncertainty. When the HVAC is turned off (18th, morning) the system rebalances and this testifies that the modeling of the HVAC proposed in this paper allows to improve the previous model.

Here Figure 8

It has to be noted that the difference in the peak value occurs during the occupied period when the inner gains contribute to modify the thermal response of the building envelope. Moreover, this deviation can be also attributed to the modeling of occupants' behavior. Indeed, also if the scheduling has been implemented according to the surveyed information, the commercial tools (ad the adopted one) models the people by means of a value of sensible and latent heat gain with a scheduled behavior in term of intensity of activity. Instead, the simulation models are not able to take into account some occasional phenomena that can occur during the lecture hours and thus discussions, recreational moments on something else that contribute to increase the indoor temperature.

Finally, this calibration allows underling the importance to use data with short time-step for understanding the real behavior of the building-HVAC system. Indeed, if the simulation models are used for optimization study it is really important a detailed knowledge of the present situation.

5.3 Alternative configurations for the microclimatic control and system operations

First of all, it occurs to define the actual control strategy that will be named "baseline" scenario in the following analysis. In the baseline model, the Air Handling Unit (AHU) regulates the VAV dampers by sending a request signal to control the airflow based on operative temperature and CO_2 concentration sensors, placed in the lecture rooms. The boiler operation control ensures to keeps the water temperature inside the tank constantly at 65°C during the weekdays and at 60°C during the weekends. There is, therefore, a constant availability of hot water which, according to the heating needs, is supplied to the heating coils of the Air Handling Units.

As previously said, in order to improve the management of heating system in the existing building and to try to not generate more energy than the amount currently demanded, some alternative control strategies for the hot water circuit have been identified, in order to minimize the energy consumption without affecting, negatively, the indoor comfort needs.

Several alternative control scenarios are defined:

- "supply": some heating curves are defined for the control of the supplied water temperature according to the value of outside air temperature;
- "tank": the heating curves are applied for the boiler control, in order to have a temperature inside the storage tank adjusted with a climatic control as a function of the outdoor temperature;
- Time: a set-back temperature value of 65°C is assigned for the water tank from 6:30 a.m. to 6:00 p.m as described in Figure 10;
- AHU: the availability of air handling unit is fixed from 6:30 a.m. to 6:00 p.m as reported in Figure 10, thus an hour earlier compared to the current timetable of activation.

Here Figure 9

Here Figure 10

More in deep the scenarios “supply” and “tank” are obtained implementing the heating curves proposed in Figure 9 (from 1 to 5) to adjust the position of the of three-way valve that mix the hot water from the tank with the water flow returning from the AHU heating coil. For this reason, five scenarios in case of “supply” control are proposed (e.g. supply1, supply2, etc) and five different scenarios for “tank” (e.g. tank1, tank2, etc..).

The selected curves, shown in Figure 9, are typical heating curves used by boiler manufactures with embedded weather control logic. The considered ones are those that allow to obtain a level of internal comfort comparable to the one obtained with the current control strategy have been considered.

Finally, to obtain better comfort conditions and energy saving, some scenarios are combined; more in detail, as explained in the following section, according to the obtained results in case of single application, the “tank” and “time” controls are combined; the “supply” is combined with “tank”; the “tank” is added to the “AHU” control.

6. Simulation results: variation of energy demands and indoor conditions

The proposed control strategies have been simulated during a period of about 75 days, from October 5th to December 20th. The simulation results have been analyzed in terms of thermal comfort and primary energy demands, as shown in Figure 11, in which, with reference to the whole period, the percentage of discomfort hours and the total primary energy demand, for all control strategies and combination of them, have been reported. In Figure 12, for each configuration, the primary energy for the working of fans with respect to the overall primary energy demands is depicted. Finally, in Table 4, the main numerical values of the obtained points in the graphs are inferred.

In particular, with reference to the indoor thermal conditions, the compliance with the comfort conditions was assessed according the EN 15251 standard [37], which defines the range 20-24°C as the thermal comfort range for operative temperature in lecture rooms, but it is possible to assume the same thermal range also for the air temperature in a moderate environment. For the calculation of the primary energy, the value equal to 2.5 kWh/kWh$_{el}$ was used as conversion factor from electric energy to primary energy, in accordance with [38]. Moreover, the value 4700 kWh/t was used as fuel calorific value according to the current used pellet in the system hot water boiler.

Here Figure 11

Here Figure 12

Here Table 4

In Figure 12, it is shown that all the alternative tested control strategies are characterized by an increase of energy consumption for the fans, because these operate with a lower supply water temperature and then of supply air, to meet the temperature setpoint inside the room. This means that the system work with a higher supply mass flow of water and air and this turns in a higher operation and energy consumption of the fans.

This happens especially when the outdoor temperature is relatively high (more than 10°C) and then the supply water temperature is also 10-15°C lower compared with the baseline scenario, and then the mass flow rate has to increase, for achieving the maximum value can be processed by the supply pump, depending on the particular considered scenario. On the other hand, when the outdoor temperature is relatively low (lower than 10°C) the supply water temperature is more or less comparable with the one of the baseline scenario and thus the supply flow rate increases, surely, but not too much.

Moreover, from Figure 12, it can be seen that the use of different slopes for the heating curves doesn't have a great effect on the total primary energy demand, but, on the other hand, it has a great effect on the energy demanded by the fans. As expected for a winter period, the higher primary energy consumption is due to the thermal needs that has an impact of 78% on the overall primary energy consumption in the simulated baseline scenario. In particular, the weight of thermal primary energy consumption on the overall once change implementing the investigated control strategies. It varies from 77% with the configuration "supply1" to 35% with the strategy "tank3", with which it could be possible obtain the minimum value of overall primary energy consumption and the maximum increase of fans energy consumption among the considered strategies. Then the weight of thermal (and fans) primary energy on the overall one decrease (increase) both due to a decrease of pellet consumption that for an increase of fans consumption and then as expected the weight of thermal primary energy is higher in the baseline configuration.

Coming back to Figure 11, it is evident that the control strategies could be divided in three groups:

- the first one is characterized both by an increase of primary energy consumption and an increase of discomfort time compared with the baseline scenario;
- the second one is characterized by a decrease of primary energy consumption, but there is an increase of time in which a thermal discomfort occurs;
- the last one is characterized by a decrease of primary energy consumption and an increase of comfortable time.

As recently confirmed by an authoritative study [39], environmental conditions in a school building aver very important for both improving the learning process and the students' wellness. About the control strategy that operates on the three-way valve, the results show that the overall primary energy consumptions increase of 2-7% compared to the baseline scenario, due to the increase of the fan energy demand. Moreover, on the basis of the considered heating curve, there is an increase of discomfort time too, from 1% to 23%, as it is shown in Figure 12.

Considering the same heating curves, but implemented for the temperature control in the storage tank ("tank"), more or less the same variation in terms of supply temperature and mass flow rate compared to the previous scenarios ("supply") can be seen. Really, this can allow a greater energy saving because the water is directly produced at lower temperature and then the thermal energy saving is higher than the increase of fan electric consumptions. Indeed, while for the previous kind of control, the hot water temperature inside the tank was almost constant around 65°C, in this control strategies it changes during the time, by following the outdoor air temperature. Depending from the used heating curve, at this group of scenarios it corresponds a decrease of the overall primary energy, from the 38% of "tank1" to the 56% of the "tank3", with an increase of discomfort time of about 2% and 19%, respectively, compared to the baseline scenario.

In the scenario "Time", the temperature trends of supply water and air are the same of the baseline scenario, because, during the AHU operation time, the two systems work in the same way. However, there is an important overall energy saving, due to the fact that, during the hours of AHU inactivity, to meet the low set-back value of temperature, the boiler doesn't work and then there is not fuel consumption. Indeed, it results that the temperature inside the storage tank is almost constant around 65°C during the operation time, while during the nights it drops, but with levels never lower

than 50°C during the weekends and therefore the boiler activation (with the following primary energy demand) is not required. Finally, through the implementation of this control strategy, it is possible to obtain, using a set-back temperature from 45°C to 20°C, an overall primary energy saving of 23% and an increase of discomfort time of 0.6%.

With the combination of " Time" and “tank”, it is possible to see a quite decrease in comfortable time. Indeed, by working at lower temperatures during the night, the system needs more time to reach the requested indoor conditions during the day. In particular, the results showed a decrease in the overall primary energy of about 35% and 46% with the control strategy “tank1&time” and “tank2&time” respectively, with a corresponding decrease of indoor comfortable time of 3% and 5% respectively compared to the baseline scenario.

By implementing the combination “tank&supply”, meanwhile, it is verified an expected decrease of primary energy demands compared to the case “supply”, but it is shown also an increase of energy demands compared to the scenarios “tank”, because - in this second comparison, due to a quite lower supply water temperature - there is an increase of the air mass flow and then an increase of primary energy consumption for fans.

For the same reason, after the weekend operation breaks, the lower supply temperature is not enough to increase the room temperature until the meeting of the setpoint temperature inside the building, with a consequent decrease of comfortable time during the whole period.

Finally, with the combination of “tank” control with an early switching on of the AHU (“tank&AHU”), it could be obtained an improvement on the comfort conditions inside the building together with a reduction of energy consumption compared to the baseline scenario. In particular, by turning on the AHU at 6:30 a.m. (and thus one hour earlier than the current time), there is an increase of about 3.9% of total primary energy but also an increase of comfort conditions time of 4.3% with reference to the whole period, due to the better achievement of comfort conditions inside the classroom before the beginning of lessons. On the other side, by working with a lower water temperature inside the water storage tank of 600 l, compared to the baseline scenario, there is both an increase in the energy consumption for the fans and a strong reduction for what concerns the pellet consumption. Finally, with these kinds of control strategies, it is possible to obtain a reduction of the primary energy demands from 32% to 46%, with a correspondent increase of comfort time in the period from 0.6% to 3.4% compared to the baseline scenario, depending to the relationship between the external temperature and water temperature inside the water storage tank.

With the control strategy “tank2&AHU”, it is possible to obtain the best trade-off between energy saving and improvement of comfort conditions, with a reduction of overall primary energy of 42.2% and an increase of comfortable time of about 3%. With the configuration “tank1&AHU”, it is possible to obtain the maximum improvement of comfortable time (3.4%), with an energy saving of 31.9% in terms of overall primary energy demand.

In general, if it would be admitted a discomfort time of maximum 10% of the occupancy period (9.9% for the strategy “tank2”), it is possible to obtain an energy saving of about 48%, with an increase of 2.85% of discomfort time compared with the baseline scenario. However, almost the same energy saving (47%) can be achieved with the combination “tank5&AHU”, that allows almost the same comfort condition compared with the baseline scenario (+0.63%). Moreover, it would be possible even to obtain a discomfort condition lower than 5%, with an energy saving around 30% compared to the baseline scenario (current condition). This is the leftmost point of Figure 12.

7. Conclusion and lesson learned

The current operation of the heating system of an educational nZEB in Ghent (Belgium), has been evaluated as the starting point to identify some possible alternatives for the HVAC control, aimed at improving both thermal and energy performance. Briefly, starting from the analysis of monitored data, in this paper a simulation energy model has

been determined and calibrated. By using the numerical model of the building, a simulation study has compared several control strategies to the baseline scenario and each other, in terms of thermal comfort and overall primary energy consumption. The case study both in term of monitoring data and simulation results allow highlighting some general conclusions that can be useful in the optimization of high efficiency building performance.

First of all, about the methodology for evaluating improvements in the HVAC operation, it is fundamental the availability of real data with a very short time step. Indeed, the analysis of annual or monthly data is not enough to detect malfunctions, to improve the control of the systems and to optimize the overall building performance, energy use and indoor comfort conditions. Hourly or sub-hourly data allow to assess the improving of existing buildings and the behavior change. Indeed, it is possible to bridge the mismatching between the expected energy performance of the buildings and the operational energy consumption in real conditions and to export strategies of management, design and information about the operational energy performance of devices and systems.

The second important conclusion concerns the management approach. Although the heating system is designed to have a low consumption and to meet comfort conditions, the overall performance could be improved by better control of the hot water generation and storage tank. Among the existing techniques, the adoption of a climatic control of HVAC determines a reduction of the overall primary energy consumption and an increase the comfortable time and thus the occupant thermal satisfaction. Indeed, rather than keep the hot water inside the tank at a quite high and constant value of temperature, over the time, without considering the time-varying nature of the heating load in a university building, it is better to implement a control curve for the supply water temperature or for the control of the temperature of the water temperature inside the storage tank, on the basis of the values assumed by the outdoor temperature. Briefly, the best compromise solution between achieving high energy savings and comfort conditions seems to require the combination of the implementation of a heating curve for the boiler control and the activation of the air handling unit an hour earlier compared to the current timetable of activation. A further improvement can be obtained by setting a timetable for the AHU's switching on, and by introducing a setback value for the control of the water temperature inside the tank.

Finally, it can be remarked that this study can be considered as a starting point to optimize the control and management of high-efficient buildings. It demonstrates how the overall performance of a building can be significantly improved using effective combination of control strategies, by underlining how the energy efficiency is sensitive to the control strategies. The role of the HVAC management becomes essential for having a high-performing building, really operating as efficiently as designed. At the same time, continuous monitoring remains the main activity for evidencing a suitable operation and, thus, for avoiding criticalities and adjusting, promptly, possible malfunctioning.

Conflicts of interest:

The authors declare no conflicts of interest.

References

[1] Directive (EU) 2018/844 of the European Parliament and of Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Official Journal of the European Union, 75-91.

[2] Directive (EU) 2010/31 of the European Parliament and of Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union, 13-25.

[3] M.S. Geraldi, E. Ghisi, Building-level and stock-level in contrast: A literature review of the energy performance of buildings during the operational stage. Energy Build., 2020, 211, 109810. https://doi.org/10.1016/j.enbuild.2020.109810

[4] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information. Energy Build., 2008, 40, 394-398. https://doi.org/10.1016/j.enbuild.2007.03.007

[5] H.B. Gunay, M. Ouf, G. Newsham, W. O'Brien, Sensitivity analysis and optimization of building operations. Energy Build., 2019, 199, 164-175. https://doi.org/10.1016/j.enbuild.2019.06.048

[6] Y. Ding, Q. Wand, X. Kong, K. Yang, Multi-objective optimization approach for campus energy plant operation based on building heating load scenarios. Applied Energy, 2019, 250, 1600-1617. https://doi.org/10.1016/j.apenergy.2019.04.164

[7] A.C. Menezes, A. Cripps, D. Bouchlaghem, R. Buswell, Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. Applied Energy, 2012, 97, 355-364. https://doi.org/10.1016/j.apenergy.2011.11.075

[8] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-the-art. Energy and Build., 2012, 55, 889-902. https://doi.org/10.1016/j.enbuild.2012.08.018

[9] E. Carlon, M. Schwarz, A. Prada, L. Golicza, V.K.Verma, M. Baratieri, A. Gasparella, W. Haslinger, C. Schmidl, On-site monitoring and dynamic simulation of a low energy house heated by a pellet boiler. Energy and Build., 2016, 116, 296-306. https://doi.org/10.1016/j.enbuild.2016.01.001

[10] S. Bechtel, S. Rafii-Tabrizi, F. Scholzen, J. Hadji-Minaglou, S. Maas, Influence of thermal energy storage and heat pump parametrization for demand-side-management in a nearly-zero-energy-building using model predictive control. Energy and Buildings, 2020, 226, 110364. https://doi.org/10.1016/j.enbuild.2020.110364

[11] M. Liu, P. Heiselberg, Energy flexibility of a nearly zero-energy building with weather predictive control on a convective building energy system and evaluated with different metrics. Applied Energy, 2019, 764-775, 10.1016/j.apenergy.2018.10.070

[12] S. Guillén-Lambea, B. Rodríguez-Soria, J. M. Marín, Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB—Quantitative analysis of the air conditioning demand, Energy and Buildings, 2017, 146, 271-282, https://doi.org/10.1016/j.enbuild.2017.04.058

[13] G. S.Georgiou, P. Christodoulides, S. A.Kalogirou, Optimizing the energy storage schedule of a battery in a PV grid-connected nZEB using linear programming. Energy, 2020, 208, 11817. https://doi.org/10.1016/j.energy.2020.118177

[14] P.Aranguren, S. DiazDeGarayo, A. Martínez, M. Araiz, D.Astrain, Heat pipes thermal performance for a reversible thermoelectric cooler-heat pump for a nZEB. Energy and Buildings, 2019, 187, 163-172, https://doi.org/10.1016/j.enbuild.2019.01.039

[15] Shu, X. Bie, H. Zhang, X. Xu, Y. Du, Y. Ma, L. Duanmu, G. Cao, Natural heat transfer air-conditioning terminal device and its system configuration for ultra-low energy buildings, Renewable Energy, 2020, 156, 1113-1121, https://doi.org/10.1016/j.renene.2019.12.152.

[16] P. Huang, H. Wu, G. Huang, Y. Sun, A top-down control method of nZEBs for performance optimization at nZEB-cluster-level. Energy, 2018, 159, 891-904, https://doi.org/10.1016/j.energy.2018.06.199

[17] M. Labidi, J. Eynard, O. Faugeroux, S. Grieu, Predictive Control and Optimal Design of Therma Storage Systems for Multi-energy District Boilers. 2014, IFAC Proceeding Volumes, 2014, 47 issue 3, 10305-10310. https://doi.org/10.3182/20140824-6-ZA-1003.01589

[18] M. Macarulla, M. Casals, N. Forcada, M. Gangolells, Implementation of predictive control in a commercial building energy management system using neural networks. Energy and Build., 2017, 151, 511-519. doi: 10.1016/j.enbuild.2017.06.027

[19] C. Dainese, M. Faè, A. Gambarotta, M. Morini, M. Premoli, G. Randazzo, M. Rossi, M. Rovati, C. Saletti, Development and application of a Predictive Controller to a mini district heating network fed by a biomass boiler. Energy Procedia, 2019, 159, 48-53. https://doi.org/10.1016/j.egypro.2018.12.016

[20] N. Aoun, R. Bavière, M. Vallée, A. Aurousseau, G. Sandou, Modelling and flexible predictive control of buildings space-heating demand on district heating systems. Energy, 2019, 188, 116042. https://doi.org/10.1016/j.energy.2019.116042

[21] J. Joe, P. Karava, A model predictive control strategy to optimize the performance of radiant floor heating and cooling systems in office buildings. Applied Energy, 2019, 254, 65-77. https://doi.org/10.1016/j.apenergy.2019.03.209

[22] M.S. Shin, K.N. Rhee, G.J. Jung, Optimal heating start and stop control based on the inferred occupancy schedule in a household with radiant floor heating system. Energy and Build., 2020, 209, 109737. https://doi.org/10.1016/j.enbuild.2019.109737

[23] D. Wystrcil, D. Kalz, Model-based optimization of control strategies for low-exergy space heating systems using an environmental heat source. In proceedings of BS2013, 13th Conference of International Building Performance Simulation Association, Chambéry, France, 2013, August 26-28.

[24] T.Q. Péan, J. Salom, R. Costa-Castelló, Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings. J. of Process Control, 2019, 74, 35-49. https://doi.org/10.1016/j.jprocont.2018.03.006

[25] S. Lee, J. Joe, P. Karava, I. Bilionis, A. Tzempelikos, Implementation of a self-tuned HVAC controller to satisfy occupant thermal preferences and optimize energy use. Energy and Buildings, 2019, 194, 301-316. https://doi.org/10.1016/j.enbuild.2019.04.016

[26] Q. Shunian, F. Fan, Z. Weijie, L. Zhengwei, L. Zhenhai, Stochastic optimized chiller operation strategy based on multi-objective optimization considering measurement uncertainty. Energy and Buildings, 2019, 195, 149-160.https://doi.org/10.1016/j.enbuild.2019.05.006

[27] Z. Guo, H. Moayedi, L. K. Foong, M. Bahiraei, Optimal modification of heating, ventilation, and air conditioning system performances in residential buildings using the integration of metaheuristic optimization and neural computing, Energy and Buildings, 2020, 214, 109866, https://doi.org/10.1016/j.enbuild.2020.109866

[28] H. S.Ganesh, H. E. Fritz, T. F.Edgar, A. Novoselac, M. Baldea, A model-based dynamic optimization strategy for control of indoor air pollutants. Energy and Buildings, 2019, 195, 168-179, https://doi.org/10.1016/j.enbuild.2019.04.022

[29] S. Guillém-Lambea, B. Rodríguez-Soria, J.M. Marín, Comfort settings and energy demand for residential nZEB in warm climates. Appli. Energy, 2017, 202, 471-486. https://doi.org/10.1016/j.apenergy.2017.05.163

[30] Modelica Association. Available online: http://www.modelica.org (accessed on May 26th 2020).

[31] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 2006, 15, 259–263.

[32] Weatherbase website: https://www.weatherbase.com/ (accessed on June 19th 2020).

[33] H. Breesch, B. Wauman, R. Klein, A. Versele, Design of a new nZEB test school building. REHVA European HVAC Journal, 2016, 1, 17-20.

[34] ASHRAE. Measurement of Energy, Demand and Water Savings. ASHRAE Guidelines 14-2014, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2014.

[35] B.J. Merema, H. Breesch, D. Saelens, Validation of a BES model of an all-air HVAC educational building. In proceeding of 10th International Conference on System Simulation in Buildings, Liege, Belgium, 2018, December 10-12. doi: 10.1051/e3sconf/201911101053

[36] M. Wetter, W. Zuo, T.S. Nouidui, X. Pang, Modelica Buildings library. J. Build. Perform. Simul., 2014, 7(4), 253–270. https://doi.org/10.1080/19401493.2013.765506

[37] European Committee for Standardization EN 15251:2007. Indoor Environmental input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. CEN: Brussels, Belgium, 2007.

[38] Flemish Government. Het Energiebesluit van 19th November 2010 - Besluit van de Vlaamse Regering houdende algemene bepalingen over het energiebeleid. Artikel 9.1.10, 19/11/2010. Available online: https://codex.vlaanderen.be/Zoeken/Document.aspx?DID=1019755&param=inhoud&AID=1129999 (accessed on May 26th 2020).

[39] P. Wargocki, J.A. Porras-Salazar, S. Contreras-Espinoza, W. Bahnfleth, The relationships between classroom air quality and children's performance in school (2020). Building and Environment, 173, art. no. 106749, doi: 10.1016/j.buildenv.2020.106749

Tables

Table 1: Properties of sensors.

Parameter	Type sensor	Accuracy
Room temperature	SE CSTHR PT100	± 0.1 °C
Air temperature	Omega PT100	± 0.10 °C
Supply temperature	SE CSTHK HX	± 0.4 °C
Water temperature	AMTRON SONIC D	± (0.30 + 0.005 * reading)
Water flow	AMTRON SONIC D	± 0.2 % reading
AHU outdoor temperature	SE PT100	± 0.10 °C
Occupancy	Acurity Crosscan Camera	± 5 %
CO_2 concentration	Vaisala GMW83	± 30 ppm + 3% reading
Outdoor temperature	Vaisala HMS82	± 0.3 °C at 20 °C
Wind velocity	Ultrasonic 2D Anemometer	± 0.1 m/s (0-5 m/s)
Wind direction	Ultrasonic 2D Anemometer	± 1°
Solar radiation	SPLite2Silicon Pyranometer	4.5 % reading

Table 2: Simulation model used for the update of the model.

Component	Simulation model
Boiler	Building.Fluid.Boilers.BoilerPolynomial
Tank	Building.Fluid.Storage.Stratified
Pumps	Building.Fluid.Movers.FlowControlled.mflow
Valve	Building.Fluid.Actuators.Valves.ThreeWayEqualPercentageLinear

Table 3: Results for MBE and CvRMSE for the calibration period.

	Troom	Tw.in	Tw.out	Ta.in	Ta.out	Wflow	Aflow	CO_2	Qheat.coil
MBE [%]	0.31	4.32	2.90	-7.24	-9.93	1.22	3.58	3.19	1.43
CvRMSE [%]	2.41	7.81	5.70	7.70	12.27	11.06	25.04	5.97	25.93

Table 4: Comparison results – numerical values.

	Primary energy tot [kWh/m^2]	Primary energy of fans [kWh/m^2]	Discomfort time [%] cold	warm
Baseline	30245	6597	6.76	0.54
Supply1	31135	7230	8.27	0.48
Supply2	31549	7846	11.10	0.04
Supply3	32699	9558	29.05	0.0
Supply4	32386	9031	24.40	0.0
Supply5	32031	8374	15.29	0.01
Tank1	19231	7290	8.50	0.50
Tank2	15714	7622	9.51	0.44
Tank3	14227	9192	25.21	0.14
Tank4	14723	8954	21.93	0.19
Tank5	14755	8183	13.24	0.40
Time	23584	6657	7.32	0.54
Tank1&Time	20143	7526	9.68	0.47
Tank2&Time	16822	7846	11.99	0.24
Supply1&tank1	19461	7470	8.68	0.48
Supply2&tank2	16193	8023	11.55	0.03
Supply5&tank5	15358	8702	16.03	0.01
Tank1&AHU	20598	7611	3.47	0.72
Tank2&AHU	17480	8065	4.01	0.53
Tank3&AHU	15635	9882	18.50	0.33
Tank4&AHU	15783	9260	14.03	0.42

Tank5&AHU	16086	8405	6.23	0.49

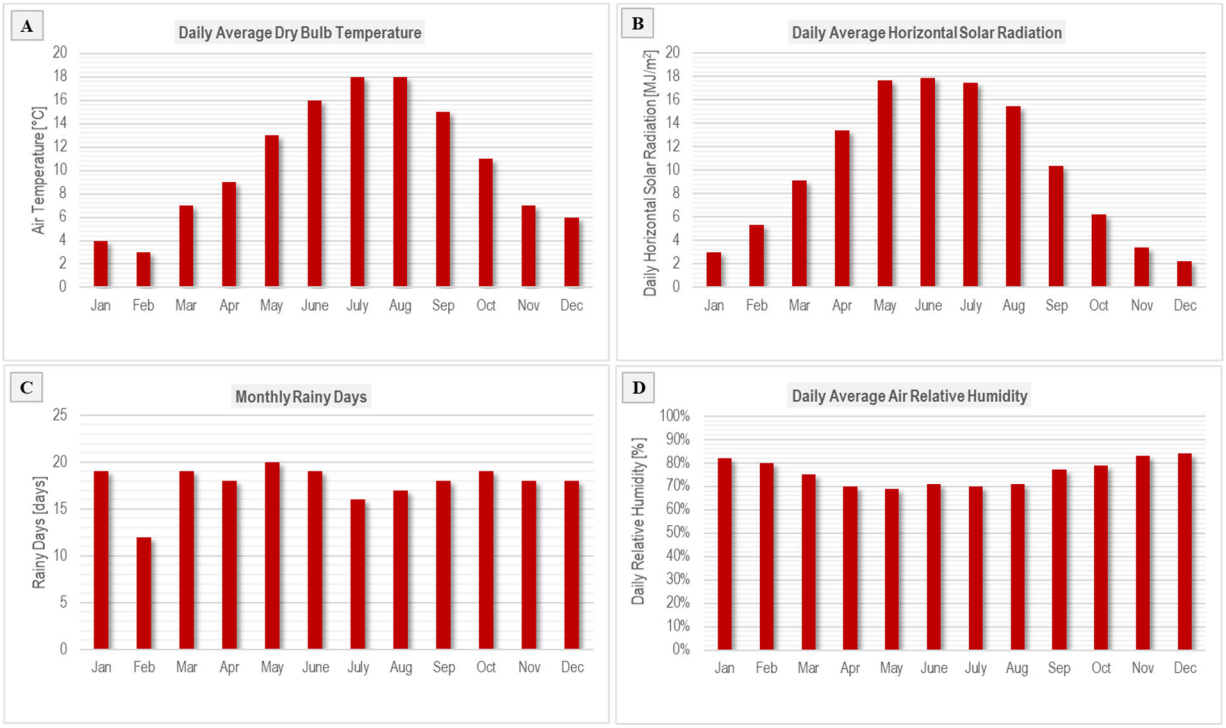

Figure 1: *Climate of Ghent (Belgium): monthly profiles of air temperature (a), solar radiation (b), rainy days (c) and air relative humidity (d); [22].*

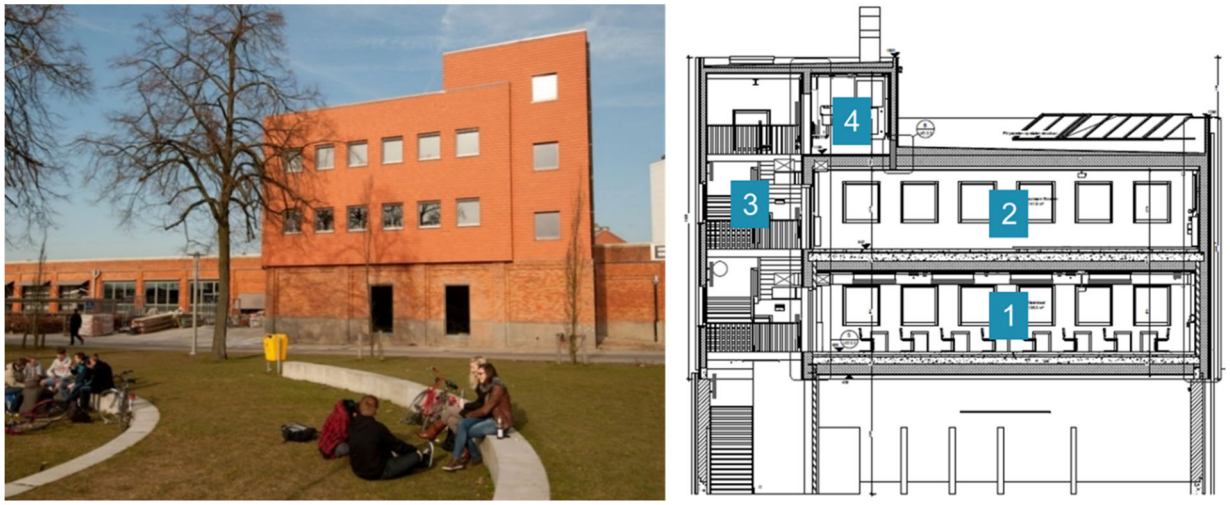

Figure 2: Left) Outside view of test lecture rooms; right) section of test building.

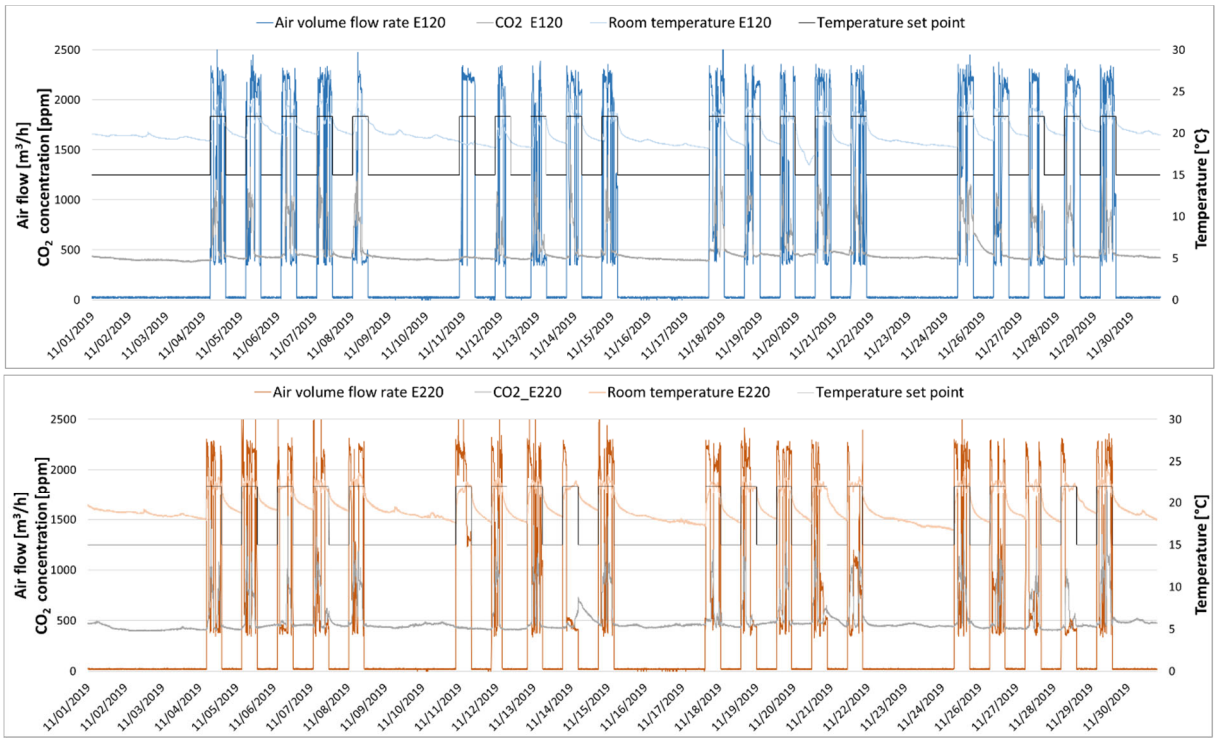

Figure 3: Supply Airflow, air temperatures and CO_2 concentrations in the classrooms (November 2019)

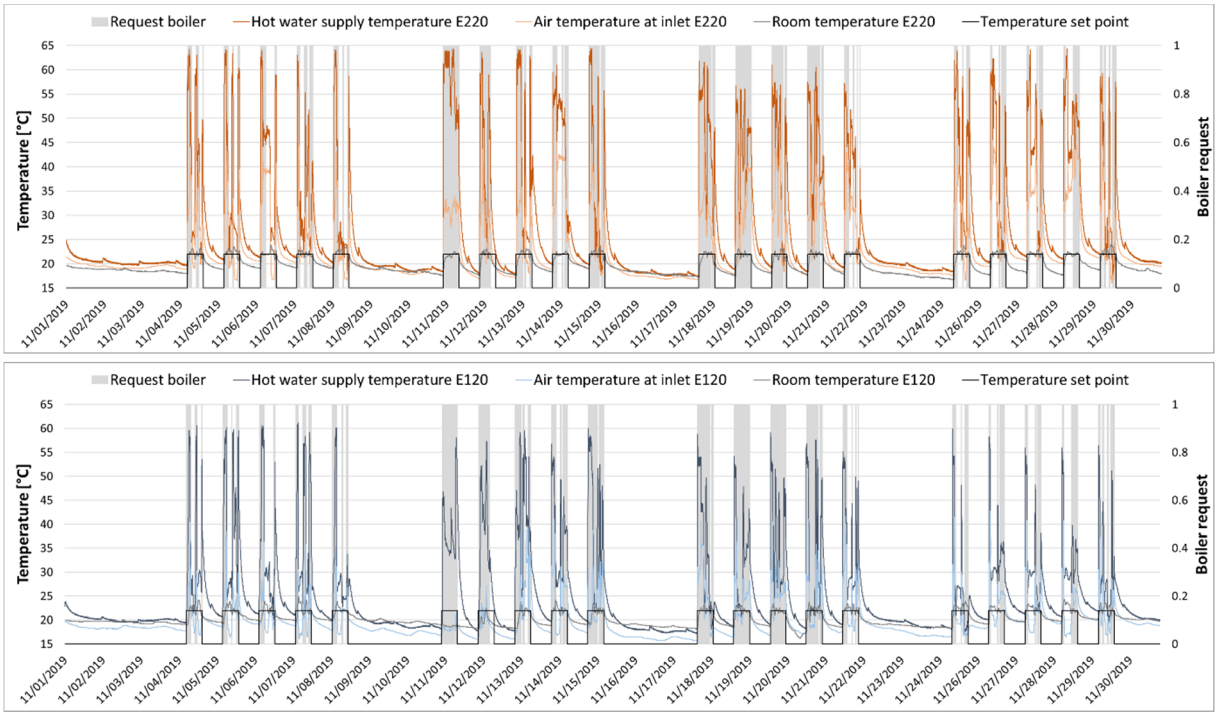

Figure 4: Boiler activation and operative temperatures (water, indoor air, AHU supply and set-points) in the classrooms (November 2019)

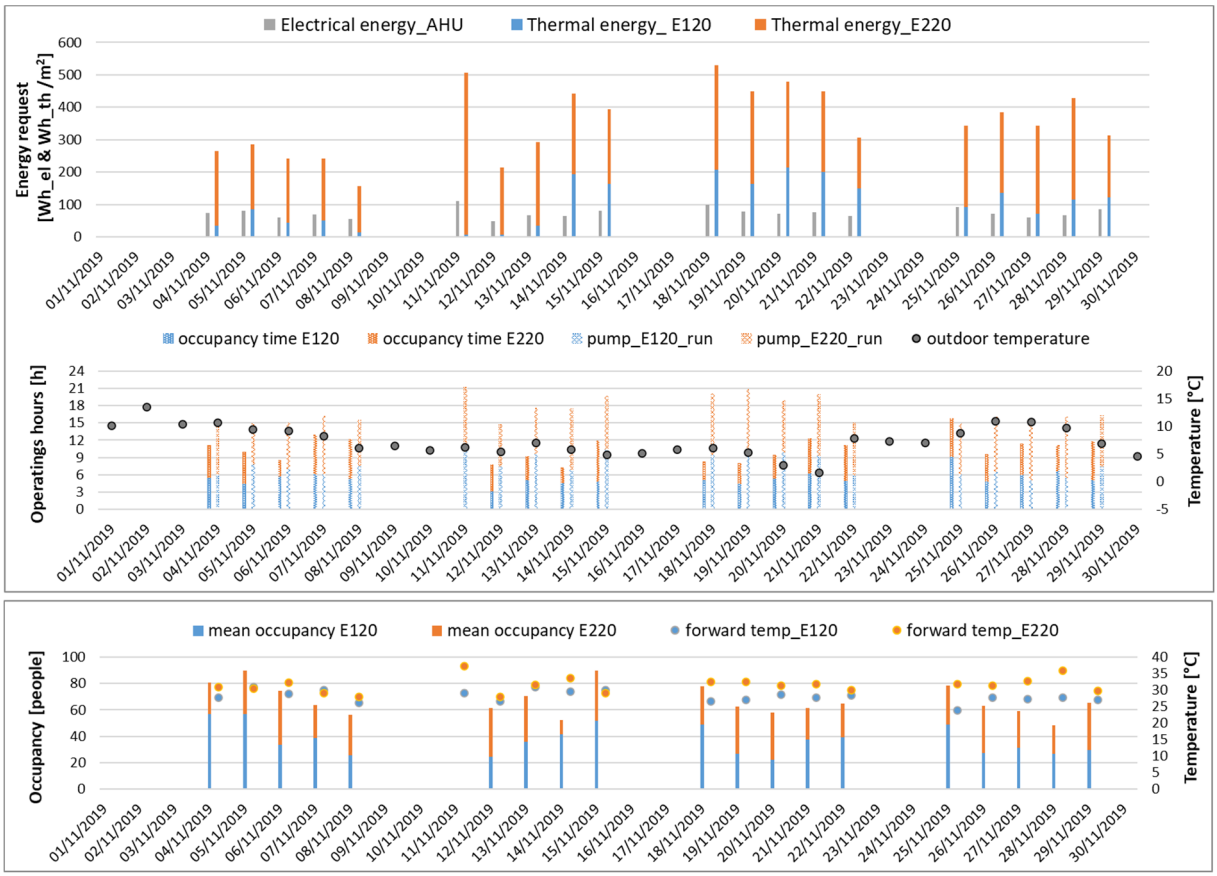

Figure 5: Current energy demands and main influent parameters (November 2019).

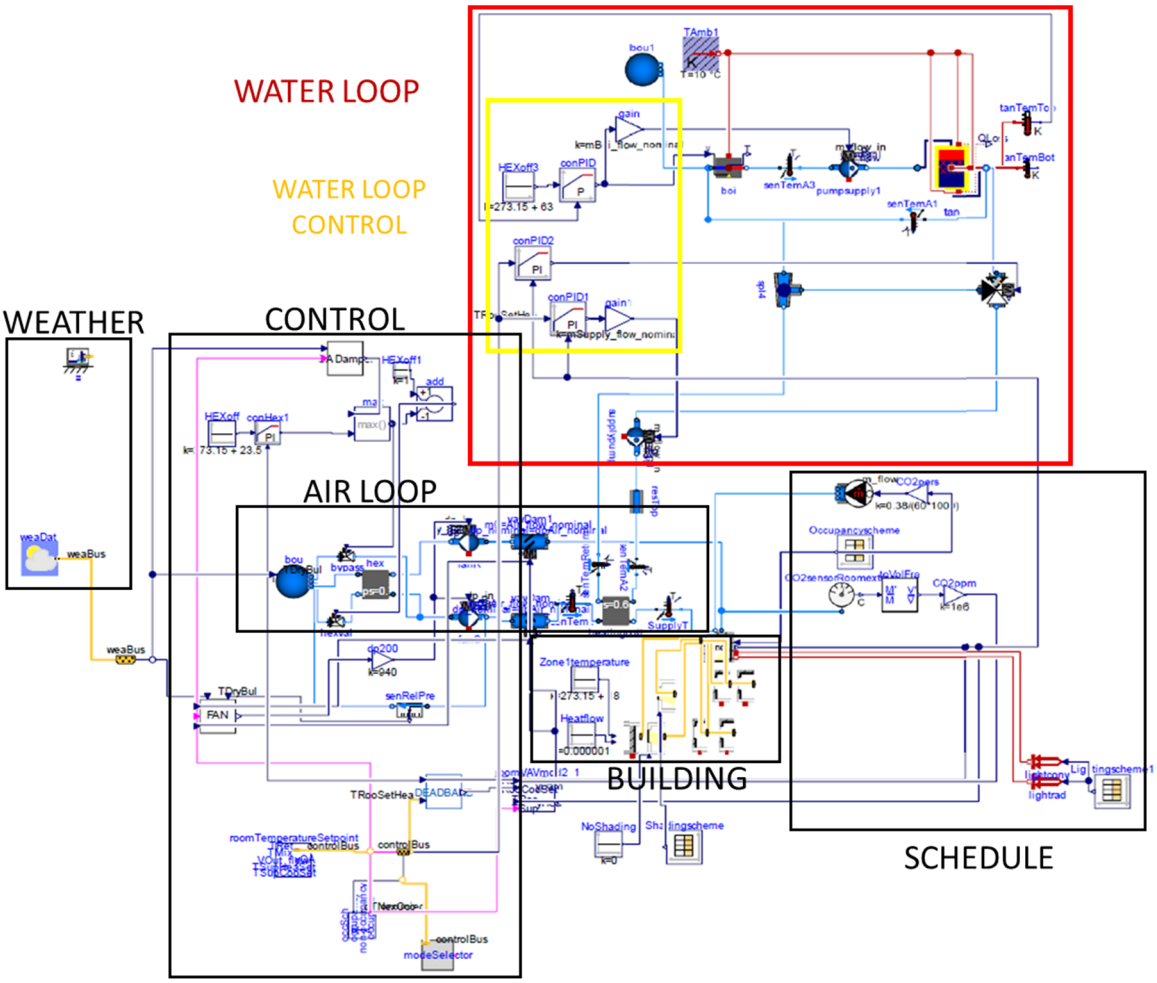

Figure 6: Modelica model of the case study building.

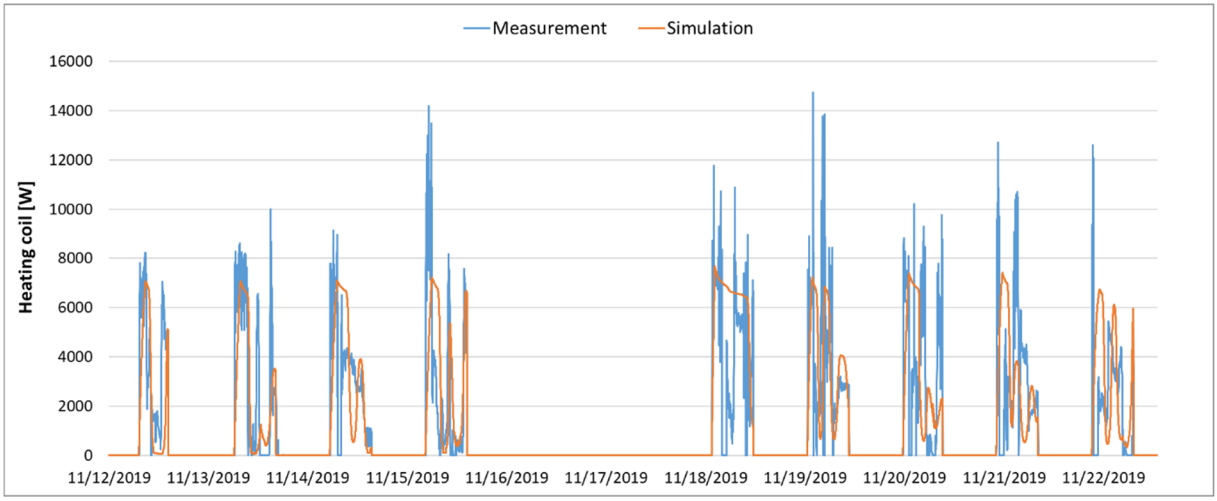

Figure 7: Results of the model calibration relatively to the heating energy transfer by the heating coil

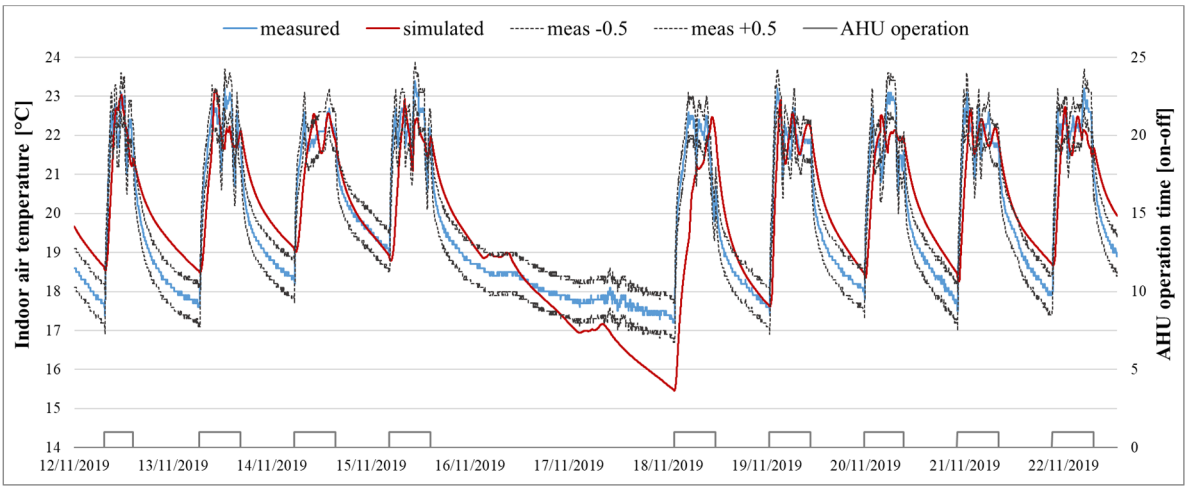

Figure 8: Results of the model calibration relatively to the indoor air temperature

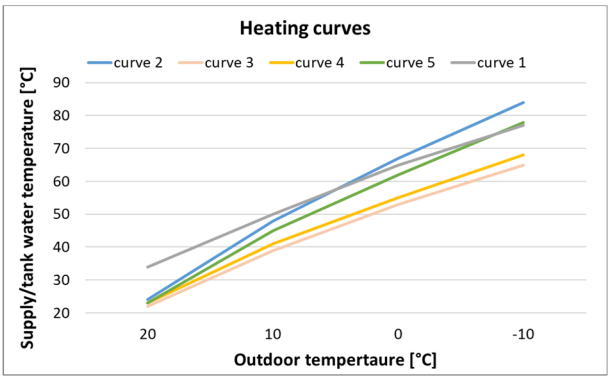

Figure 9: Heating curves for control strategies based on climatic corrections

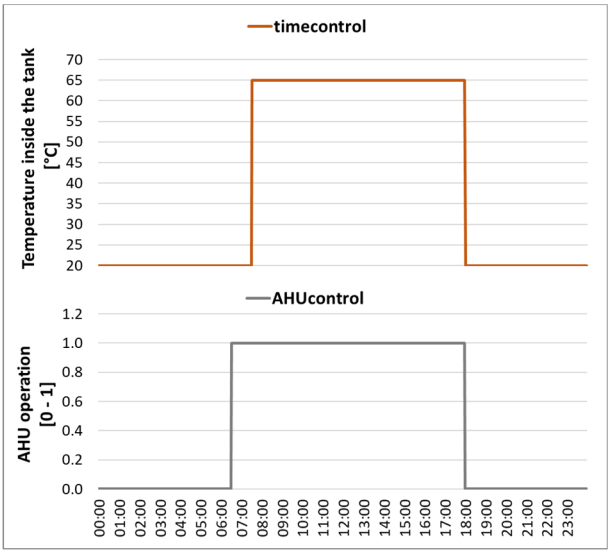

Figure 10: Time schedules for selected control strategies

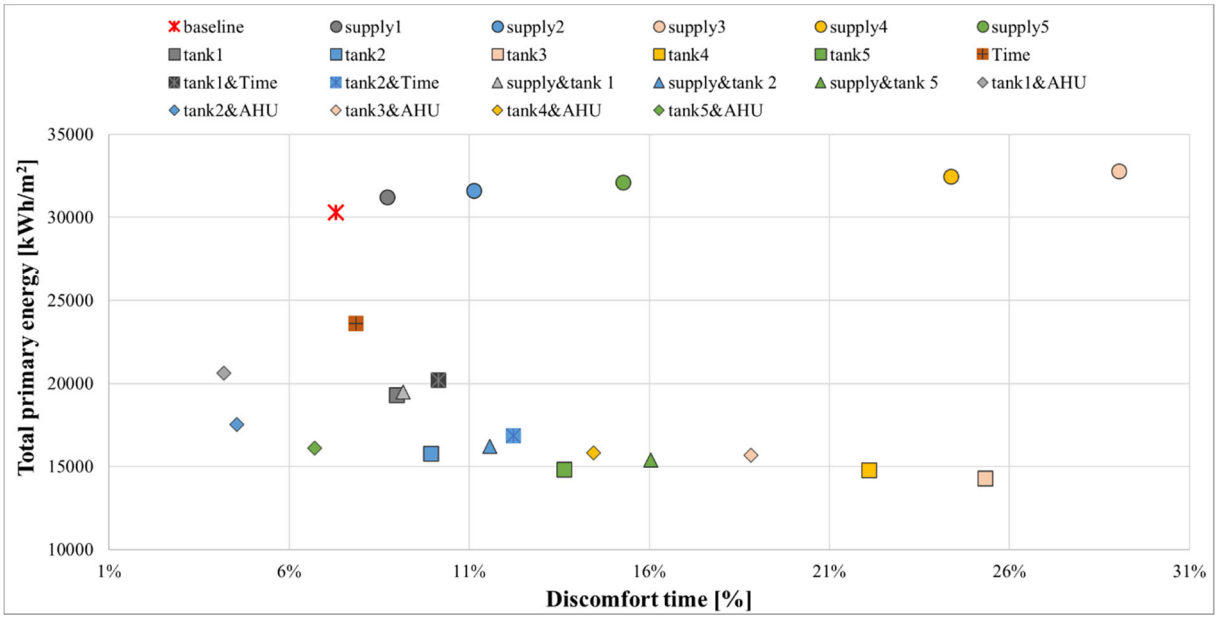

Figure 11: Comparison of results, total primary energy demand and the indoor discomfort time

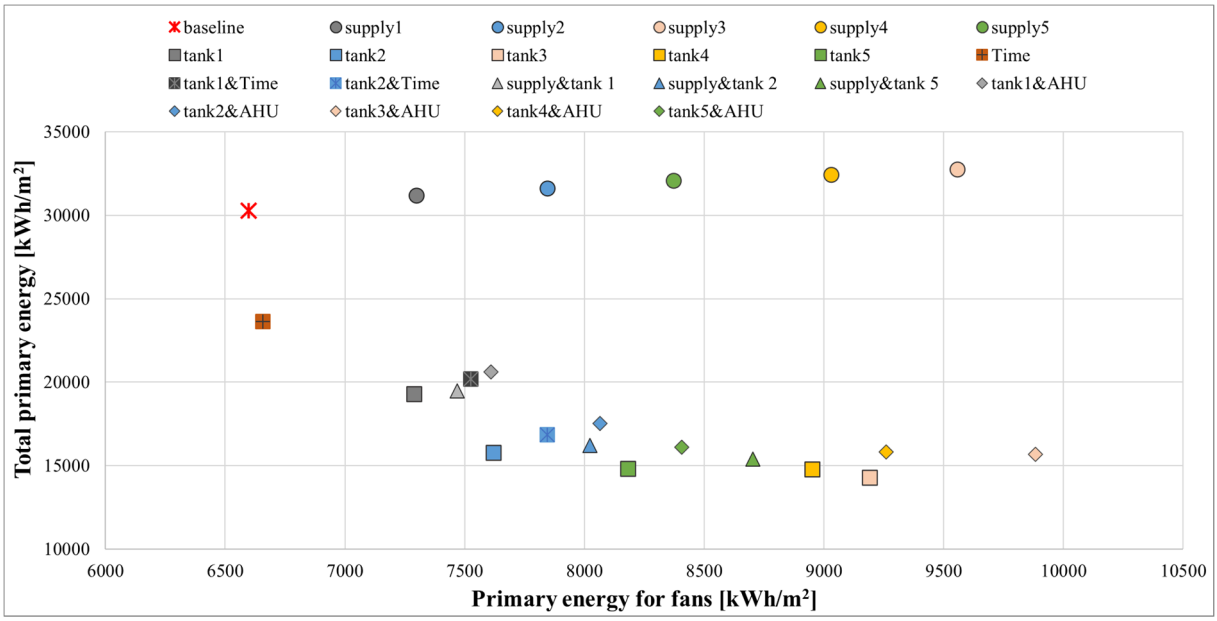

Figure 12: Comparison of results, total primary energy and primary energy for the AHU fans