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# Performance Evaluation and Improvement of a Newly-Renovated Danish School Building (Retro-commissioning)

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## Abstract

In this study, we analyse and evaluate the energy performance of a Danish school building 4 years after its renovation. The structure of the following paper follows four phases, which include Planning, Investigation, Implementation and Hand-off. In the Planning phase, the objectives of the retro commissioning are set based on the Owner's Project Requirements. The Investigation phase aims to analyze how the building and its systems are performing in terms of energy use and indoor environmental quality. The Implementation phase includes dynamic building simulations, which target to analyze different solutions and their impact on the energy consumption and indoor environmental quality in the building. Description of the final solution for optimization is included in the conclusion (Hand-off phase) of this paper.

## Introduction

Driven by the increasing requirement of energy consumption reduction and indoor environment improvement, the renovation necessity of old office buildings is rising in recent years.

Optimizing the building service system is very important for the future energy comsumption. Denmak has a plan to become independent on fossil fuels by 2050 (Boman, 2015), therefore minimizing the energy consumption of the building systems is important.

A non-residential building that has existed for decades often experiences several renovations. Ideally, the most recent renovation should fix, if not all, most of identified problems and improve the building performance for a long period to make the project beneficial. In practice, the renovation of a building often comprises with the budget and building owners' preferences, and consequently settles on a partial or unthoughtful solution. Commissioning that includes both the renovated and non-renovated parts of the building is therefore necessary to conduct periodically after the delivery of the project. When problems occur during the evaluation of a renovation project after several years, it is preferred to solve them in a cheap and feasible way. Though either the problems or the solutions can be case-dependent, the objective of this study is to find out problems 4 years after a recent renovation and corresponding solutions and to seek potential recommendations for general implications. This retro commissioning process is based on ASHRAE Guideline 0-2005 (ASHREA, 2005) and California Commissioning Guideline 2006 (Haasl & Heinemeier, 2006).


*Figure 1 Ground floor plan of the building*

The building object of this study is located in the main campus of Aalborg University, Denmark. The building is built in 1976 and covers a total floor area of 4185 m $^2$ distributed principally on the ground floor level with a free floor level access. The building consists mainly of offices, classrooms and other common areas, such as lunchrooms, with a central corridor layout, see *Figure 1*.

In 1996, the building had undergone a major renovation, mainly with the replacement of windows, addition of thermal insulation in the roof construction and improvement of the heating system. Afterwards, in 2012 the building went through a new refurbishment, which included the replacement of windows, addition of skylights (in order to improve natural ventilation and daylight) and the installation of a new HVAC system in part of the building.

A central building management system (BMS) is controlling the heating and ventilation systems, as well as the lighting in the building. The BMS is an advanced system for both controlling and monitoring the equipment in the building. It has the possibility of recording data, such as energy usage of the ventilation units, operative temperature in the rooms, $CO_2$ concentration and others. With the recorded data, it is possible to evaluate the current performance of the building and its installations. The data is also basis for suggesting adjustments for the HVAC system. The HVAC system follows schedules for individual rooms (meeting rooms, group rooms and conference rooms), which are pre-booked online. For instance, the mechanical ventilation system and heating system will turn on half an hour before a class and turn off when the class is over.

All offices in the building (marked with light blue in *Figure 1* and *Figure 2*) have natural ventilation. The occupants there can control the windows, skylight openings, curtains, as well as the radiators. We conducted an online questionnaire-based survey for the naturally ventilated zone of the building in May 2016, and 17 out of 71 occupants replied (corresponding to 24%). The reviews of thermal comfort and visual comfort are from 'Neutral' to 'Satisfied'.

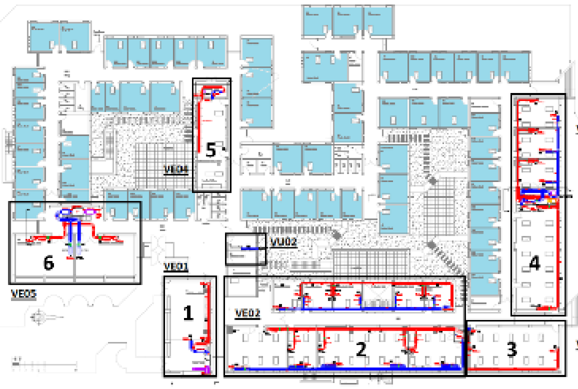



*Figure 2 All the offices are naturally ventilated (in light blue), and the rest common rooms are ventilated by six ventilation units (marked in numbers)*

In *Table 1* are listed the requirements for energy performance, indoor thermal comfort, indoor atmospheric comfort and visual comfort, for the 2012 renovation. These requirements are representing the Owner's Project Requirements. The retro-commissioning process uses this requirement to evaluate the current performance of the building.

*Table 1 List of parameter requirements*

| **Category** | **Demand** | **Source** |
|---|---|---|
| **ENERGY** | | |
| **Windows <1.1 W/m²K (2 layers thermo-glass)** | | Kravspecifikation – Sept. 2011 |
| **Solar Shading (Connected to CTS/weather station)** | | Kravspecifikation – Sept. 2011 |
| **Annual energy use per heated floor area: Buildings built between 1961 and 2006 should fit in Class C or better.** | Class A 2010: ≤ 71.3+1650/A<br>Class B: ≤ 95.0 +2220/A<br>Class C: ≤ 135 + 3200/A | BR2010<br>BR2008 |
| **Max. air change through infiltration:** | 1.5 [l/s/ m²] at ΔP = 50 Pa | BR2010 - 7.2.1(4) |
| **THERMAL COMFORT** ***The following requirements are specified for Category II/B building*** | | |
| **Operative temperature winter:** | 20˚C ≤ Top ≤ 24 ˚C | DS 474 (2.3) |
| **Operative temperature summer:** | 23˚C ≤ Top ≤ 26˚C | DS 474 (2.3) |
| **Max. mean air velocity in occupied zone:**<br>**Heating season**<br>**Cooling season** | <br>v = 0.18 m/s<br>v = 0.20 m/s | CR 1752 |
| **Vertical temperature difference:** | PD < 5%; ΔT < 3 ˚C (at 1.1m and 0,1m) | DS 474 (2.3) |
| **Warm or cool floor:** | PD < 10%;<br>19 ˚C ≤ $T_{fl.}$ ≤ 29 ˚C | DS 474 (2.3) |
| **ATMOSPHERIC COMFORT** ***The following requirements are specified for Category II/B building*** | | |
| **$CO_2$ level** | $CO_2$ should not exceed 1000 ppm for extended periods | BR2010 (6.3.1.3) |
| **Minimum air flow:** | 10 l/s/person plus 1 l/s/m ²floor area<br>7 l/s/person plus 0.7 l/s/m² floor area | CR1752 Class I |
| **In the case of mechanical ventilation:** | Minimum heat recovery of 75 % with rotary heat exchanger | Kravspecifikation – Sept. 2011 |
| **In the case of VAV:** | Max. power consumption for air movement 1800 J/ m³ | BR 2015 8.3(9) |
| **Extraction systems without supply:** | Max. power consumption for air movement 800 J/ m³ | BR 2015 8.3(9) |

| VISUAL COMFORT | | |
|---|---|---|
| **Daylight factor** | DF > 2% at workplaces | BR10, 6.5.2 (1) |
| **Lighting** | $E_m$= 200 lx at 0.8m height in offices<br>$E_m$= 100 lx in corridors<br>$E_m$= 500 lx in meeting rooms with video conference; 200 lx normal use | Kravspecifikation – Sept. 2011 |

## Literature review

Building commissioning has played a major role as a quality assurance process, which aim is to ensure that the building and its systems meet the needs and the requirements of the owner. This process is running parallel with the existing phases of the building process. The two main advantages of the commissioning are energy and non-energy benefits, depending on the owner's project requirements. There are numerous researches looking into the benefits of commissioning and their financial values. However, the most comprehensive example is from the United States, which is not a surprise as this country is one of the leading nations in implementing and developing the commissioning process. According to this study, if the focus is mainly on energy saving then after applying the retro commissioning process to existing buildings, the energy usage is lowered by 16% for building systems and the cost for this commissioning was $3, 23 per m2. The same research outlines that by implementing the non-energy benefits, which are improved and ensured - thermal comfort and indoor air quality, the cost is lower and the expected payback time was around one year. (Mills, 2009)

## Field measurement and Simulation (Investigation phase)

During visit of the building, we identified few problems regarding the building envelope. Not the entire part of the external wall is brick; concrete beams are visible both from the outside, and create cold bridges since they are not insulated (*Figure 3, a*). The windows and doors in the corridors are in bad condition. There are cracks in frames of some windows (*Figure 3, b*).

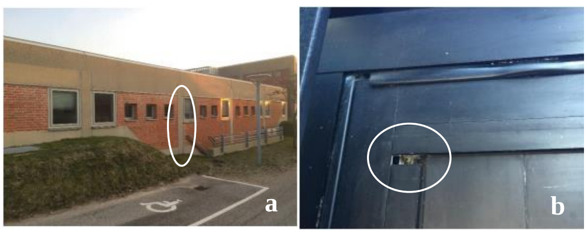



*Figure 3 Uninsulated concrete beams (a) and cracks in window frame (b)*

The air distribution principle in the mechanically ventilated part of the building is displacement ventilation. Displacement ventilation is known to be very effective due to the temperature and concentration vertical gradient in the ventilated zone. However, in the current building part, the ceiling is too low to generate a decent stratification height for the occupants, which may result in high contaminant concentration in the occupied zones. Another observation is that furniture is blocking some of the inlet diffusers (*Figure 4*). In the central BMS, we observed that the set points of the ventilation system and the heating system are the same (22$^o$ C). The consequence is later analysed by numerical simulations.

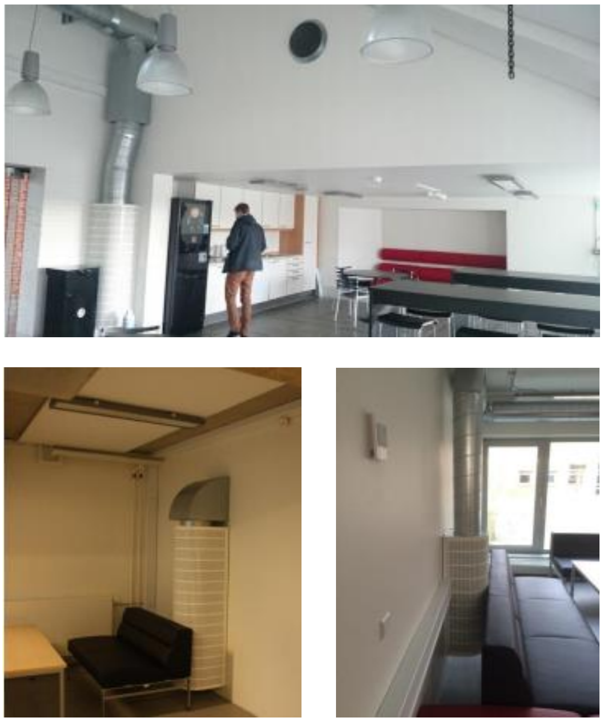
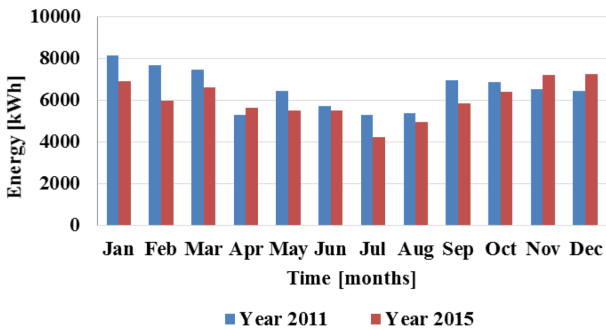


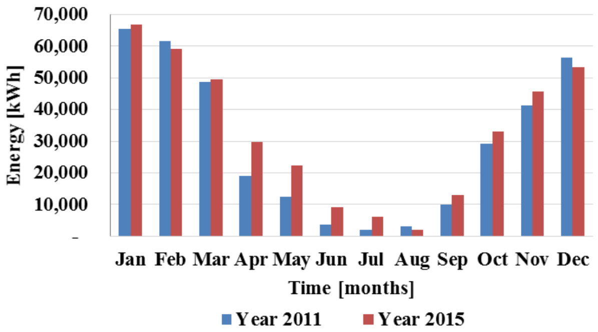
*Figure 4 Misuse of displacement ventilation*

In *Graph 1*, *Graph 2* and *Graph 3* are plotted the recoded data for electricity consumption, heating and domestic hot water for 2011 and 2015. The central BMS is measuring and recording the data.



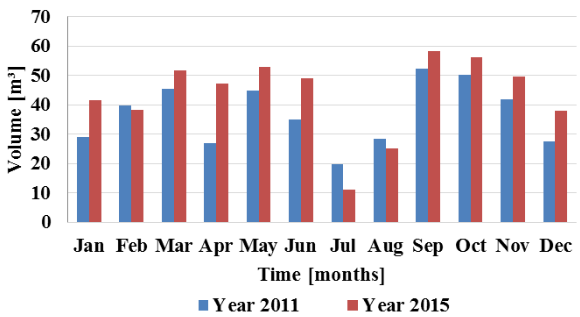

*Graph 1 Electricity consumption in 2011 and 2015*

The electricity consumption takes into consideration electricity use for ventilation units, lighting, and plug load (computers, coffee machines, etc.). The total electricity consumption has decreased by approximately 8% after the 2012 renovation. The cause of this reduction is the implementation of the control system for the ventilation and lighting in the building.




*Graph 2 Heating consumption in 2011 and 2015*

The heating consumption has increased by approximately 10%. The difference in people schedule would probably only be a small portion of this increase since the usage of the rooms are similar as before renovation. It is interesting to point out that the need for heating has increased in summer. This could be due to a lower outdoor temperature during the summer in 2015 than in the summer 2011.




*Graph 3 Hot water consumption in 2011 and 2015*

The hot water consumption has increased by approximately 18% due to the new toilets and a larger number of occupants.

The data alone cannot show the actual improvement of the renovation in terms of energy consumption, since many boundary conditions were not the same in the two years. Namely different weather conditions that determine both the behaviour of the heating system and the occupants; varying people load before and after renovation, hence the increase in water consumption, and so on. These results are contradicting with the expectations – that the building is using more electricity due to the installation of a new mechanical ventilation system and less heating due to better windows.

In order to analyse in detail, a Danish building simulation software, BSim, is used for calculating and analysing indoor climate conditions and energy consumption of the building. The thermal simulation core of BSim is "tsbi", and it is developed in 1985 (Kim B. Wittchen, 2013). Danish Design Reference Year (DRY_2013) is the hourly outdoor weather data, used for the yearly simulations. Seven rooms are chosen for simulations to represent the whole building and the dynamic variation (time step = 1 sec) of $CO_2$ concentration, operative temperature and relative humidity will be calculated based on the occupants' schedule and weather data. In *Table 2* and *Figure 5* are indicated the location and some parameters of the rooms. The purpose of choosing eight examples rooms is to cover the parts of the building based on different orientation and usage of the rooms.

*Table 2 List of Rooms selected for numerical simulations*

| Room | People Load | Area | Volume |
|---|---|---|---|
| | [-] | $[m^2]$ | $[m^3]$ |
| **Room 1** | 60 | 94 | 248 |
| **Room 11** | 54 | 99 | 317 |
| **Room 21** | 58 | 97 | 304 |
| **Room 37** | 18 | 32 | 102 |
| **Room 66** | 50 | 63 | 181 |
| **Room 101b** | 1 | 16 | 46 |
| **Room 117** | 1 | 16 | 46 |
| **Room 123** | 36 | 59 | 247 |

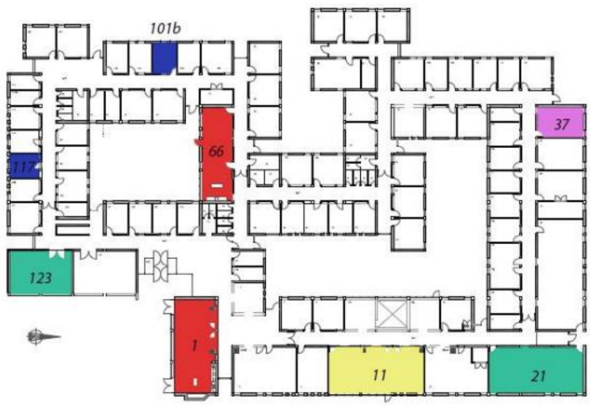



*Figure 5 Locations of selected rooms*

Room 123 is southeast oriented and used as an example in this paper. It is a seminar room typically used for lectures and exams. The room is fitted with new mechanical ventilation system. *Figure 6 illustrates* BSim 3D model of the room.

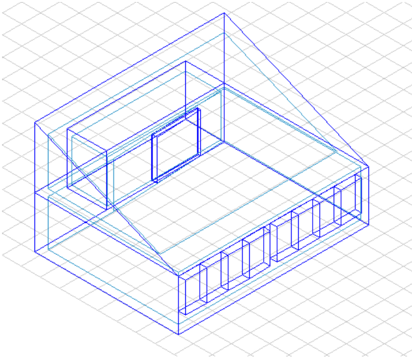


*Figure 6 BSim model of Room 123*

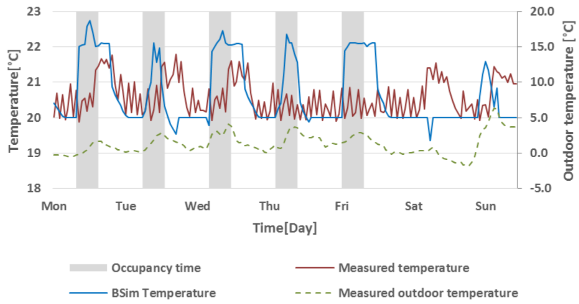
For validation of the model, the set points for heating and cooling (*Table 3*) include day and night according to the HVAC control. Night set point is for both night and unoccupied hours.

*Table 3 Heating, cooling and $CO_2$ set points in the example room 123*

| Parameter | Set point |
|---|---|
| Heating set point for occupied hours 08:00-17:00 | **22.0 ℃** |
| Heating set point for unoccupied hours 17:00-08:00 | **20.0 ℃** |
| Cooling set point | **22.1 ℃** |
| $CO_2$ set point for ventilation | **1000 ppm** |

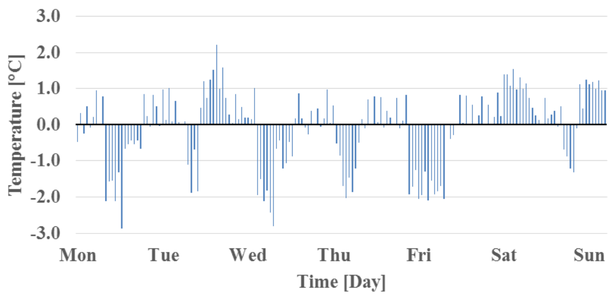
The booking schedules are a basis of developing the daily profiles used in the simulations. For this room (123) the scheduled booked lecture takes place from 17:30 to 21:00, which is outside the normal occupied hours. Therefore, the ventilation system is controlled and working according to the booking schedule and the design people load of 38 people.

*Graph 4* presents the results of the simulation compared to the measured data of operative temperature. It is visible from the graph that the BSim model is able to achieve much steadier operative temperature during periods with a low amount of delivered heat gain (no or little solar gain, equipment loads and unoccupied hours in general). This is because BSim regulates the heating output for each time step. However, this is not how it happens in reality, as the thermostats installed on the radiators are not able to regulate the heat output in the same extent. The main reason for that is the fact that sensors have a delay time (accuracy) from the moment of receiving and moment of transmitting the data. Another reason is the precision of the thermostatic valve in terms of minimum temperature range it can sense. Therefore, small changes in the delivered heat or in the transmission loss will not instantly result in increase or decrease of the heat output, and simultaneously will result in more temperature fluctuations.



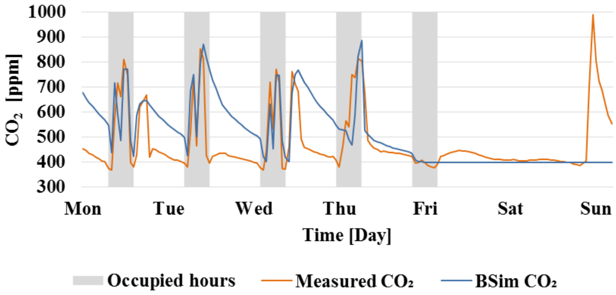

*Graph 4 Measured and BSim operative temperature in Room 123 on 7th – 14th of March 2016*

To validate the model, the deviation of the operative temperature between the measured and simulated values is calculated. From *Graph 5*, it is visible that the temperature differential between the real measurement and the simulation is not greater than 1 ℃, which is approximately 11% for deviation of 1 ℃ and 21% for deviation of -1 ℃. As this fluctuation is not so significant, the model is further used for simulation of a whole year IEQ.

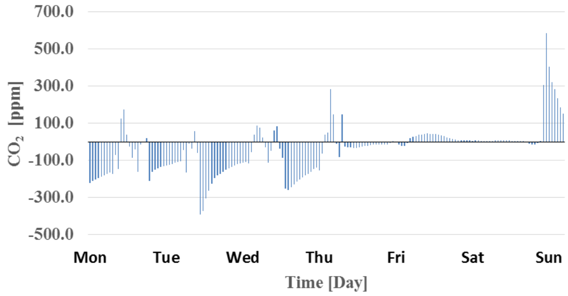



*Graph 5 Operative temperature deviation in Room 123 on 7th-14th of March 2016*

*Graph 6* shows the measured and simulated $CO_2$ profiles in Room 123. The $CO_2$ profile from BSim dilutes slower during unoccupied hours than the measured level, since the schedule for ventilation in BSim model does not include ventilation during unoccupied hours. It is not clear from the measured data if the ventilation is working at nights, since the $CO_2$ decays are the same every day.



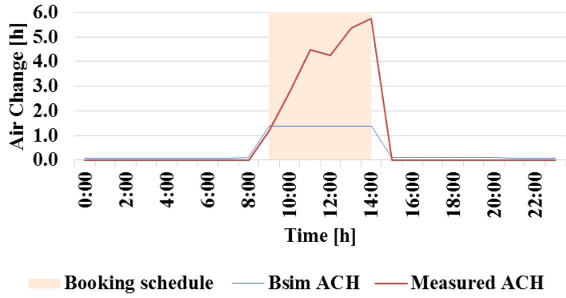

*Graph 6 Measured and simulated $CO_2$ profile in Room 123 on 7th – 14th of March 2016*




*Graph 7 $CO_2$ profile deviation in Room 123 on 7th-14th of March 2016*

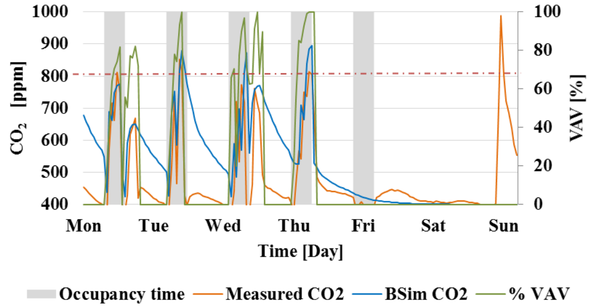
The resulted deviation of the $CO_2$ profile between the measured values and the results from the simulation is in *Graph 7*. The fluctuation between 100 ppm and -100 ppm is considered acceptable, which results in 8% and 33% deviation respectively from the total values. This fluctuation is deemed acceptable as such difference in $CO_2$ concentration will not have a great impact to the people and will not affect the results of the simulation significantly. Therefore, the model is considered validated and it is further used for analysis of the IEQ for whole year simulations.

In *Graph 8* is plotted the measured data for VAV control system for Room 123 for one day. This measured data is then analysed and compared to the simulated air change rate in the room, in order to get a better understanding of the operation of the ventilation system, when the booking schedule is a control strategy. The graph represents how the measured ACH fluctuates according to the VAV control, while the BSim model ACH is stable for the booking period.

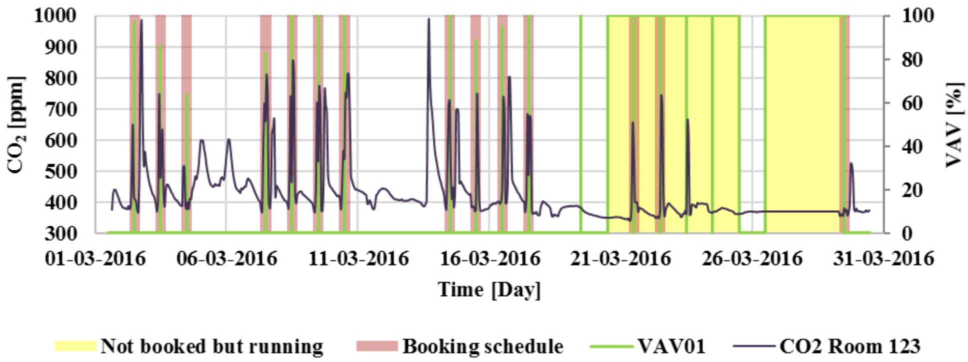



*Graph 8 Example of VAV control for Room 123 for Tuesday 8th of March*

The BSim model operates based on the set point for $CO_2$ level of 1000 ppm. Therefore, we need to investigate, if the design set point of 1000 ppm corresponds to the measurements. As a result, it is found that the ventilation starts running at 100% (VAV – 100%), when the $CO_2$ concentration is higher than 800 ppm as shown in *Graph 9*. Therefore, the $CO_2$ concentration set point in BSim is 800 ppm instead of 1000. This change of the set point contributed positively to the ACH according to the $CO_2$ concentration. Further investigation for Room 123 includes simulations for a period of a month.




*Graph 9 Measured and simulated $CO_2$ profile in Room 123 in Week 10*



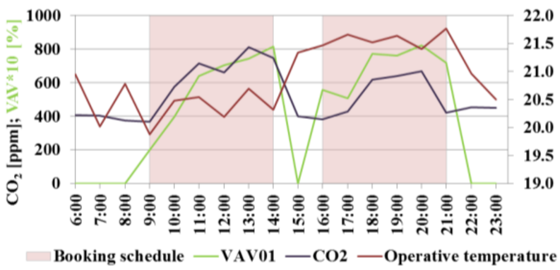

*Graph 10 Measured $CO_2$ level and VAV % in Room 123 in March 2016*

When looking at the whole-month measurements for March for Room 123, as shown in *Graph 10*, the ventilation system starts to operate at 100% once the $CO_2$ level reaches 800 ppm. It can be concluded that the ventilation system is controlled based on a range for $CO_2$ concentration, such as working at full load, when the $CO_2$ level is in the range between 800 ppm and 1000 ppm.

From the provided records with data, it is clear that the BMS is off for the holidays in order to prevent extra energy consumption. Therefore, for the period from 21st to 29th of March, estimated values are in the graphs for all parameters and all rooms recorded.

## Discussion and result analysis (Implementation and Hand-off phases)

The investigation through simulation and experiments (measurements) shows that the cooling and heating set points of the control system have the same values, which will create an environment with constant temperature, but at the same time will increase the energy consumption. However, constant temperature is only required in buildings like laboratories and hospitals, while in the case having a range between heating and cooling set points will result in reduction of the consumed energy. Another drawback of the control system is the fact that booking schedules have priority for the activation of the ventilation system, thus, causing the ventilation system to be running even when there are no people in the room (when people don't come for the booked period).




*Graph 11 VAV control according to booking schedules*

*Graph 11* shows an example of such scenario, and it illustrates that the increase of airflow in the room is only due to the booking schedules. This is so because, the $CO_2$ levels never reach the set point of 1000 ppm and the room temperature is less than the maximum of 22 ℃ for the cooling mode to start. The reader should be aware that *cooling mode/set point* in this project is the temperature at which the ventilation will start working at a maximum level (100% of VAV); the cooling of indoor air is by air change with supply temperature lower than the ambient temperature.

In order to optimize the building's performance in terms of indoor environment and energy consumption, dynamic simulations in BSim are performed with focus on ventilation set points for cooling, as well as set points for inlet air temperature. Four scenarios were analysed for the two parameters (cooling set point and inlet air temperature), and compared to the initial performance of the building. The first parameter to analyse is the cooling set point, since the existing control of the ventilation system has the same heating and cooling set points, which is not energy efficient for the system. In *Table 4* are indicated the set points that were tested with BSim simulations. The aim of the simulations of different scenarios was to find the optimal cooling set point that can both keep the thermal comfort level, and reduce the energy consumption. The inlet air temperature is always the same as Scenario 0 in this simulation.

*Table 4 New set points to test with simulations*

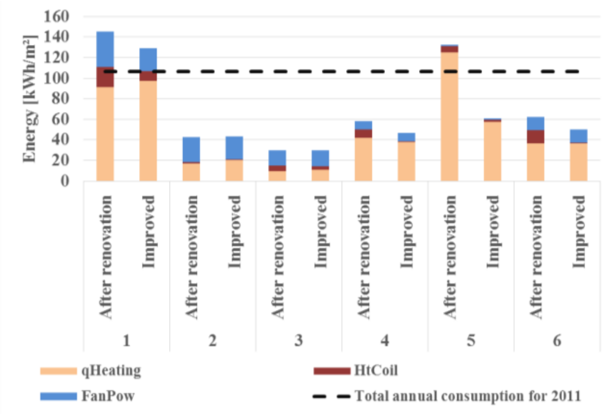
| Set points | Scenario 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| **Heating** | | | | | |
| **Occupied hours** | 22 | With the aim of analysing the influence of separate parameters, the other set points are kept the same as in Scenario 0 (Existing conditions). | | | |
| **Unoccupied hours** | 20 | | | | |
| **Weekend / holiday** | 20 | | | | |
| **Ventilation** | | | | | |
| **Cooling set point** | **22.1** | **23** | **24** | **<u>25</u>** | **26** |
| **Inlet air temperature** | **21** | **20** | **<u>19</u>** | **18** | **17** |

Simulation results showed that the ventilation fans' electricity consumption decrease with increasing cooling set point. It can be explained by the fact that the ventilation needs to work less, when higher temperature is allowed in the room. The overheating hours (counted only for occupied hours), however, can become a problem if the cooling set point is increased. In the case, the optimal solution for a cooling set point is 25 ℃, where the reduction of the energy consumption results in 3.3%.

Second parameter to analyse is the set point for inlet air temperature. Simulation results showed that when decreasing the set point for inlet air temperature, the energy needed for room heating is increasing. In reality this outcome is also expected, as the room heating set point should be maintained, and if there is no consumption for the heating coil, the radiators will compensate the remaining heating demand. Analysing simulation results, the optimal inlet temperature set point is 19 ℃. This conclusion is based on several considerations: the existing ventilation principle is DV, which requires a lower inlet air temperature than the ambient air; the amount of overheating hours is decreased by 44 hours above 26 ℃ and 13 hours above 27 ℃ compared to the initial condition. Choosing even lower inlet air temperature set point (e.g. 18 ℃) would increase the energy consumption by 10.5%, which is almost doubled from the case with inlet of 19 ℃. The decrease of overheating hours with inlet of 18 ℃ has a very little difference from the case with 19 ℃ inlet, therefore, the energy cost for this low inlet temperature is considered unjustified.

*Table 5 Improvement solution*

| | U-value [W/m²K] | g-value [-] | Eref [kWh/m²/year] |
|---|---|---|---|
| **Windows** | 1.00 | 0.49 | -13.4 |
| **Door corridor** | 1 | 0.49 | -11.8 |
| **Skylights** | 1.4 | 0.49 | 8.7 |
| | **Occupied hours** | **Unoccupied hours** | **Preheating period [h]** |
| **Heating set points** | 22 | 18 | 2 |
| **Cooling set points** | 25 | - | - |




*Graph 12 Comparisons of the annual energy consumption between the existing conditions and the solution*

The final suggestion for improvements is summarized in *Table 5*. *Graph 12* represents a comparison of the energy consumption between the initial conditions and the new found from the simulations with the different set points. The energy consumption includes the room heating (qHeating), preheating the inlet air (HtCoil), and electricity for running the fan for ventilation system (FanPow). In addition, a detailed overview of how much the energy consumption will decrease or increase after running the heating and ventilation system with the new set points are in *Table 6*. For most of the rooms, this change of set points will result in energy saving, where the biggest saving is in Room 66. However, these changes of the set points will influence the indoor environment. Therefore, in *Table 6* are the simulation results for the temperature during occupied hours above 26 ℃ and 27 ℃ through the whole year. It can be noted that there will still be overheating in some of the rooms. Thus, passive solutions such as natural ventilation should be analysed in the rooms with temperatures above 26 ℃ for more than 100 hours and above 27 ℃ for more than 25 hours. The rooms that exceed these guideline values are Room 11, Room 21, Room 37 and Room 123.

*Table 6 Difference in energy consumption and hours below or above allowed operative temperature and $CO_2$*

| | **Difference in energy consumption from Scenario 0** | **$T_{op}$ < 20 ℃ [h]** | | **$T_{op}$ > 26 ℃ [h]** | | **$T_{op}$ > 27 ℃ [h]** | |
|---|---|---|---|---|---|---|---|
| | | **S 0** | **S 1** | **S 0** | **S 1** | **S 0** | **S 1** |
| **Room 1** | -11% | 0 | 0 | 53 | 47 | 17 | 13 |
| **Room 11** | 2.5% | 0 | 0 | 340 | 215 | 164 | 116 |
| **Room 21** | 4.8% | 0 | 0 | 299 | 253 | 163 | 152 |
| **Room 37** | -5.5% | 0 | 0 | 228 | 110 | 142 | 68 |
| **Room 66** | -45% | 0 | 0 | 48 | 49 | 15 | 13 |
| **Room 123** | -2.6% | 0 | 0 | 245 | 140 | 108 | 73 |

## Conclusion

By going through the four phases of retro commissioning, the results indicated that by optimizing the control of the HVAC system and the natural ventilation, it showed a reduction of the energy consumption in the investigated rooms. Conclusion is that the optimal use of natural ventilation will reduce the risk of overheating, thus fulfilling the regulation for operative temperature during occupied hours.
The combination of all the improvements, considering HVAC set points and introduction of passive solutions will have a positive effect on the energy consumption for the chosen rooms, as well as the IEQ.

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