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Published in:
Science and Technology for the Built Environment

DOI:
10.1080/23744731.2019.1693207

Published: 15/03/2020

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Vand, B., Martin, K., Jokisalo, J., Kosonen, R., & Hast, A. (2020). Demand response potential of district heating and ventilation in an educational office building. *Science and Technology for the Built Environment*, *26*(3), 304-319. https://doi.org/10.1080/23744731.2019.1693207

Demand response potential of district heating and ventilation in an educational office building

Behrang Vand, Kristian Martin, Juha Jokisalo, Risto Kosonen and Aira Hast

Abstract

This study examines the influence of demand response control strategies on thermal conditions, indoor air CO_2 concentration, heating energy cost and consumption in an educational office building heated by district heating system in a cold climate. The real-time pricing-based demand response is applied for space heating, heating of ventilation and adjustment of air flow rates. The ventilation analysis covers both constant and variable air volumes systems. The applied demand response algorithms regulate room air temperature set points for space heating, temperature set point for supply air and CO_2 set point adjusted with the variable air volume ventilation system. The accepted room air temperature range was 20-24.5°C and CO_2 concentration within 800-1200 ppm. This study was conducted with the validated dynamic building simulation tool IDA ICE. The results illustrate that the maximum yearly savings by demand response of space heating and ventilation with the constant air volume ventilation system are around 3 and 6% for the heating energy consumption and heating energy cost, respectively. For the variable air volume system, the heating energy consumption, heating energy cost, electricity consumption and electricity cost can be saved by demand response control up to 8, 11, 9 and 2%, respectively.

Keywords: Demand response control, district heating, rule-based control, dynamic energy pricing.

Nomenclature

CO_2	carbon dioxide
ppm	parts per million
EMS	energy management system
AHU	air handling unit
CAV	constant air volume
VAV	variable air volume
CHP	combined heat and power
TRY	test reference year
MET	metabolic rate
ACH	air change per hour
IDA ICE	IDA Indoor Climate and Energy
CS	control signal
DH	district heating
HEP	hourly electricity price
HEP_{avr}^{+p+q}	average of future hourly energy prices determined from hour p to hour q
T_{air}	indoor air temperature
$T_{avr,24\ out}$	average outdoor temperature of the previous 24 hours
$T_{lim,out}$	limiting outdoor temperature
$T_{SH,max}$	maximum air temperature set point
$T_{SH,min}$	minimum air temperature set point
$T_{SH,norm}$	normal air temperature set point
$T_{AHU,min}$	minimum supply air temperature set point
$T_{AHU,med}$	median supply air temperature set point
$T_{AHU,max}$	maximum supply air temperature set point
$T_{AHU,norm}$	normal supply air temperature set point
$C_{CO2,set}$	CO_2 concentration set point
$C_{CO2,max}$	maximum CO_2 concentration
$C_{CO2,design}$	design CO_2 concentration
Q_v	ventilation airflow
$Q_{v,max}$	maximum ventilation airflow
$Q_{v,min}$	minimum ventilation airflow

1. Introduction

Building sector accounts for almost 35% of the final energy consumption and almost 25% of the total greenhouse gas emissions (International Energy Agency, 2016). Thus, buildings play an important role in preventing global climate change by diminishing the final energy consumption and greenhouse gas emissions of buildings. Demand response, as an option for peak load management, refers to flexible demand where end users are able to reduce and shift their energy consumption, manually or through an automation system (McKenna & Thomson, 2014; Vand et al., 2019; Sehar et al., 2016; Shan et al., 2016; Li & Xu, 2016). Demand response is able to take part in load management programs to diminish peak demand and avoid exposure of its infrastructure to critical strains (Claessens et al., 2018; Bozorg Chenani et al., 2017 and 2018; Valogianni & Ketter, 2016). For instance, Alimohammadisagvand et al., (2016a) and Alimohammadisagvand et al., (2018a and 2018b) studied different demand response control algorithms for a residential house for different heating systems. They found that the heating energy consumption and cost can be decreased by 12% and 15% depending on the heating system.

For a building, demand response can reduce the energy consumption during expensive energy prices and/or rescheduling the use of energy in the direction of cheap energy prices, for instance, Yoon et al., 2016 and Wang, 2016. One important object on the demand response control from the building owner or user point of view is to preserve thermal comfort and indoor air quality (Alimohammadisagvand et al., 2015; Kim & Norford, 2017; Arabzadeh, 2017). Due to influence of room air temperature on heat demand of buildings, multivariate temperature set points can moderate energy demand (Chang et al., 2016; Nassif & Moujaes, 2008; Cetin et al., 2016). Dynamic pricing is considered to be the most efficient pricing program to combine with the demand response (Hu et al., 2015). Mishra et al., (2019) demonstrated the effects of centralized demand response control of district heating on indoor thermal conditions and perceived thermal comfort by using field tests in a university building. Thus, the performance of demand response on buildings can be improved with smart control strategies.

District heating is widely used as an environmentally friendly solution for providing heating services for the built environment in many European countries (Lund et al., 2014). In Finland, 49% of the people are living in buildings heated with district heating system. The district heating is Finland's most popular heating method and its share of the heating market is 46% (Energy District Heating, 2017). Sameti and Haghighat (2017) presented that the district energy systems have the capacity to get benefits such as practical, environmental and safety by taking advantage of large poly-generation energy conversion technologies. They introduced different types of optimization problems, constraints, techniques and optimization tools used in district energy systems. Vandermeulen et al., (2018) reviewed techniques to quantify flexibility in district heating and showed the need for more advanced control strategies. Swing Gustafsson et al., (2018) presented that a challenge is to have enough available power of district heating in different periods. They concluded to reduce peak demand of district heating and at the same time produce more electricity by using combined heat and power strategy. Coss et al., (2018) proposed a holistic energy service model for design optimization of energy supply. They applied a multi-objective optimization for the district heating system and demand side using the load deviation index, and found that the demand side management can contribute to higher performance of such systems. D.Korkas et al., (2015) studied a simulation-based optimization approach for the design of an energy management system (EMS) in grid-connected photovoltaic-equipped microgrids with heterogeneous occupancy schedule. They showed that the proposed approach behaves efficiently by considering the occupancy information, intelligently and automatically changing the energy demand of each building according to the occupants' behavior. They developed (D.Korkas, 2016) the EMS for joint demand response management and thermal comfort optimization in microgrids equipped with renewable energy sources and energy storage units. They found that the energy costs are reduced and at the same time thermal comfort of the occupants is maintained.

In general, demand response has been applied for buildings heated by electricity, for instance, direct electric heating or heat pumps. As significant number of buildings in some countries like Finland, Sweden, Denmark etc. are heated by district heating, interest and need of demand response on district heating is nowadays increasing (Kontu et al., 2018). So far, only few studies have been conducted on this subject. Dominković et al., 2018; Le Dréau & Heiselberg, 2016; and Kontu et al., 2018 studied the dynamic behavior of buildings and the effect of the heat load cuts on costs. They also presented that the peak load cut depends on the thermal mass and insulation level of envelope, the climate conditions and the acceptable range of operative temperatures indoors. Kontu et al., (2018) presented a city scale heat demand model to examine the effect of several demand side management strategies on both a heat producer and costumers. Their results showed that the value of demand side management for a district heating companies remains less than 2% in cost savings. As well, they noted that the district heating price model should be developed to make demand side management more attractive to district heating customers. Moreover, few studies have been conducted on the influence of demand response on the whole energy system (Dominković et al., 2018; Difs et al., 2010; and Romanchenko et al., 2018). For instance, Cai et al., (2018) investigated demand response within the district heating network of Copenhagen public works (21 customer nodes) and they resulted energy cost saving up to 11%.

Rotger-Griful et al., (2016) proposed a simple and general model of ventilation system based on affinity laws and they showed the demand response potential on fan power. Martin et al., (2018) studied the influence of the demand response on indoor air temperature and CO_2 concentration in an office building with both Constant Air Volume (CAV) and Variable Air Volume (VAV) ventilation systems. They found that the thermal comfort can be maintained and the CO_2 concentration level is also possible to maintain at the acceptable level.

At the moment, few studies have been focused on applying demand response on the district heating system with dynamic energy prices. Thus, there is a gap of knowledge of the benefits of demand response on energy cost with district heating. As well, because most of the studies have concentrated only on a single house, it is important to analyze the influence of demand response of district heating on a large commercial building. The influence of demand response actions on energy cost, room air temperature and indoor air CO_2 concentration have not been shown earlier for buildings heated by district heating. The novelty of this research is to introduce rule-based demand response strategies for both space heating and ventilation systems of an educational office building where dynamic price tariff of district heating and electricity are utilized.

2. Methodology

2.1 Structure of the simulation study

The demand response control algorithms were executed in the IDA ICE building simulation tool. The developed control algorithms made decisions on set points of space heating and ventilation based on the room air temperature, outdoor temperature, indoor air CO_2 concentration and the energy price trend of the district heating and electricity. Figure. 1 shows the scheme of the simulation process.

2.2 Hourly district heating and electricity prices

The dynamic tariffs were defined according to the model of hourly prices for district heating and electricity, as shown in Figure. 2. The district heating price used in this study represents a price of a regular district heating producer in Finland and it contains energy, taxes and a dynamic transfer fees (Figure. 2a). The hourly district heat prices were calculated based on a district heating system that consists of a combined heat and power (CHP) plant and heat-only boiler as described in Salo et al., 2019. The CHP plant could also be used to produce only heat and the fuels used in the plant were wood and peat. The heat output of the CHP plant was 50% of the peak heat demand and at each hour, the heat demand that cannot be covered only with the CHP plant was produced with the oil-fired heat-only boiler. For each hour, the cheapest heat production option (i.e. whether the CHP plant produced only heat or both heat and electricity, and whether the heat-only boiler was also needed) was chosen, so that the hourly heat demand was met. The hourly heat demand was calculated using a weather data from the Finnish test reference year (Kalamees et al., 2012). In addition, e.g. electricity consumption, losses as well as risk and profits were taken into account in the costs increasing the marginal costs by 21%. Based on these hourly prices, a 12-hour moving average price was calculated for each hour.

The wholesale electricity price was taken from Nord Pool Spot (2015) and taxes and a dynamic transfer costs (Fortum, Agency of Electricity in Finland, 2019) are added to it (Figure. 2b). The dynamic transfer cost and electricity tax were determined, so that their annual revenue is at the current level. The dynamic transfer cost was calculated based on the relative hourly power demand.

2.3 Weather data

The Finnish test reference year (TRY2012) (Kalamees et al., 2012) was used as a weather data for dynamic simulations in this study. The Test Reference Year (TRY) weather file represents a typical weather data of a year. The TRY is, therefore, an assembled composite of average months from a database of historical weather data. The used weather data contains detailed hourly data of outdoor temperature, wind velocity, relative humidity, solar radiation representing the current climatic conditions of Southern Finland (Kalamees et al., 2012). These data were cumulated by monitoring and recording a 30-year period (1980–2009) at the weather station of Helsinki-Vantaa airport.

2.4 Building simulation tool – IDA ICE

This study is simulation-based, and it was performed by IDA Indoor Climate and Energy (IDA ICE) building performance simulation software (Sahlin, 1996). IDA ICE 4.7 is a simulation application for the multi-zone and dynamic study of indoor air quality, thermal comfort as well as energy use in buildings. The IDA ICE was also validated in several studies, for example (Equa Simulation AB, 2010a; Alimohammadisagvand et al., 2016b; Bring et al., 1999; International Energy Agency Solar Heating & Cooling Programme, 1999; and Equa Simulation AB, 2010b) which shows strong justification to use the IDA ICE in this study.

3. Demand response control simulation

3.1 Building description

The studied building is an educational office building at Otakaari 4, Espoo, Finland (Aalto University campus) originally built in 1960s, and renovated in the early 2000s. The building has five floors and a heated net floor area of the building is 8616 m^2. Only the fourth floor of the building was modelled and studied, and the heated net floor area of the studied floor is 586 m^2. Figure. 3 shows the studied floor layout.

3.1.1 Building structure

Main features of the building structures and thermal bridges of the studied building are shown in Table 1. All the load bearing structures of the building are massive concrete structures. Also, internal walls are massive meaning that the thermal mass of the building is high and the building is well suited for demand response study. The losses of thermal bridges were assumed based on the Finnish building code D5 (2012).

The original 2-pane windows were renovated by replacing an inner window pane by an argon filled low-emissivity glazing element. The new glazing elements of the windows facing south or west were also equipped with solar protection. Solar heat transmittance (g-value) of south and west facing windows is 0.38 while for the rest of the windows it is 0.59.

Air leakage rate of the building (n_{50}) was estimated to be 1.6 ACH, based on the study by Vinha et al. (Vinha et al., 2009).

3.1.2 Technical systems

The studied building is heated by district heating. A heat distribution system of the building is a water radiator heating system. The dimensioning heating power for space heating and ventilation of the 4th floor is 40 kW, respectively at a design outdoor temperature -26 °C. The efficiency of the district heating substation is set to be 97 % considered as a regular value for substations in large buildings (D5 Finnish code of building regulation (2012)). The inlet water temperature for water radiator system is controlled in accordance with the outdoor temperature, and dimensioning the supply and return water temperatures are 70/40 °C at the design outdoor temperature (-26 °C) and room air temperature (21 °C).

The ventilation system of the building is mechanical supply and exhaust ventilation with VAV control in meeting rooms and lecture halls and CAV in other types of zones. The main characteristics of the ventilation system of the 4th floor is presented in Table 2.

3.1.3 Internal heat loads

Since data on actual occupancy of the studied building was not available, simulated occupancy rate was based on literature. According to the literature review, the occupancy rate can vary quite a lot within educational buildings. Manicca et al., (2013) stated an average occupancy level of 46 % and Page et al., (2008) noted a typical range of 35 – 40 %. Moreover, Baumann and McClintock (1993) reported occupancy rates of 30 – 75 %. Because of that, this study used two dissimilar occupancy scenarios, including 40 and 70 % which can be thought to present typical work places. The occupied-hours were between 8:00 – 16:00. The maximum number of occupants in the studied floor was between 1 and 4 occupants per room. The activity level and clothing of the occupants were assumed to be 1.2 MET and 0.75 ± 0.25 clo representing heat load of 126 W/occupant (D3 Finnish code of building regulation (2012)). The installed lamps in the rooms had an average specific heat load (7.5 W/m^2) and the equipment heat load was assumed to be 50 W/occupant.

3.2 Rule-based demand response controls

The demand response control strategy is to heat up the building by increasing temperature set points of space heating and ventilation supply air if the district heat price trend is increasing, because the energy price is going to be more expensive in future. According to the strategy, the heat energy stored in the structures is used by lowering the set points when the district heat price trend is decreasing, because the energy price is going to be cheaper in future. Moreover, air flow rates of the VAV ventilation system are controlled according to the trend of both district heat and electricity prices. If either of prices is decreasing, air flow rates is decreased by increasing CO_2 concentration set point. Otherwise, higher air flow rates are used.

In this study, it was presumed that the district heating and electricity prices for a 24 hours ahead are known. A control signal (CS), which describes the price trend, was defined according to the price data. The trend of district heating and electricity prices can be increasing, decreasing or flat and it was specified by the values: +1, -1 or 0, respectively. The method presented by Alimohammadisagvand et al., (2018b) and shown in Eq. (1) generated the control signal and then it was used in the building simulation software. The control signal was calculated based on the momentary hourly energy price (*HEP*) of district heat or electricity, average of future hourly energy prices determined from hour p to hour q ($HEP_{avr}^{+p,+q}$) and parameters defined as down (negative) or up (positive) constant marginal values. With low marginal values, price is classified as cheap more often and the price trend as rising, and vice versa for high marginal value.

$$If \begin{Bmatrix} HEP < HEP_{avr}^{+1,+24} + marginal\ value_{down} \\ or \\ HEP_{avr}^{+6,+12} < HEP_{avr}^{+6,+24} + marginal\ value_{up} \end{Bmatrix}, \qquad Then \qquad CS = +1 \tag{1}$$

$$Elseif\ HEP > HEP_{avr}^{+1,+24}, \qquad Then \qquad CS = -1$$

$$Else\ CS = 0$$

$$End\ If$$

3.2.1 Demand response control with the CAV ventilation system

The demand response control, presented in Figure. 4, controlled space heating and supply air temperature set points in the cases of CAV ventilation system.

The room air temperature set point of space heating was determined matching to the future price trend of the district heating as follows:

- During the cold season when the outdoor temperature is cold enough (average outdoor temperature of the previous 24 hours ($T_{avr,24\ out}$) is lower than limiting outdoor temperature ($T_{lim,out}$)) and the price trend is growing (CS=+1), the control system charges extra heat into the thermal mass of structures by adjusting the maximum temperature set point ($T_{SH,max}$) to space heating. But if the price trend is reducing (CS=-1), the demand response control system sets the minimum temperature set point ($T_{SH,min}$) to space heating. Otherwise, if the price trend is flat (CS=0), the building is heated up by using normal temperature set point ($T_{SH,norm}$).

- During the warmer season, when ($T_{avr,24\ out} > T_{lim,out}$), the room air temperature set point is normal ($T_{SH,norm}$) or minimum one ($T_{SH,min}$) if the future price trend of the district heating is decreasing (CS=-1).

Ventilation supply air temperature set point was determined as follows:

- During the cold season, when ($T_{avr,24\ out} < T_{lim,out}$), the supply air temperature set point has three constant alternatives, including minimum ($T_{AHU,min}$), median ($T_{AHU,med}$) or maximum one ($T_{AHU,max}$) if the district heating price trend is growing, flat or reducing, respectively.
- During the warmer season, when ($T_{avr,24\ out} > T_{lim,out}$), the normal supply air temperature set point ($T_{AHU,norm}$) is used, which is adjusted by the control curve (see Figure. 5) as a function of exhaust air temperature.

3.2.2 Demand response control on the VAV system

Figure. 6 shows the flowchart of the demand response control on the VAV system. It controlled the space heating temperature set point, supply air temperature set point and ventilation airflow by adjusting the CO_2 concentration set point of the zones in line with the *HEP* of district heating and electricity.

The principle of the space heating and ventilation supply air temperature controls are similar to the demand response control on the CAV system (see section 3.2.1).

The CO_2 concentration set point ($C_{CO2,set}$) was increased if the *HEP* trend is decreasing ($C_{CO2,set}=C_{CO2,max}$). Otherwise, the CO_2 concentration set point was defined in accordance with the design value ($C_{CO2,design}$). The CO_2 concentration set point was adjusted as input values to the building simulation software. Then, momentary CO_2 concentration was automatically calculated and monitored for each zone in the IDA ICE.

The ventilation airflow (Q_v) was determined as follows:

- If the room air temperature exceeds 24.5 °C and outdoor air is warm enough ($T_{avr,24\ out}$ > 0°C), the ventilation airflow rate was increased to the maximum value regardless of the *HEP* trend (Q_v=$Q_{v,max}$). This prevents too high room air temperatures through warmer periods.
- During the unoccupied period (4 PM<Time<8 AM), the airflow rate of ventilation is at the minimum level (Q_v=$Q_{v,min}$).
- During the occupied period (8 AM<Time<4 PM), both future *HEP* of district heating and electricity are assessed. If the price trend of hourly district heating or electricity is decreasing, ventilation airflow rate was lower on average, because the higher CO_2 concentration set point ($C_{CO2,max}$) is used. Otherwise the airflow rate is higher on average, since ventilation system tries to maintain lower CO_2 concentration level without exceeding the design set point of CO_2 concentration ($C_{CO2,design}$).

3.3 Used set points for demand response controls

The acceptable room air temperature range was selected according to the latest classification of indoor environment by the Finnish society of indoor air quality (Finnish Society of Indoor Air Quality (FiSIAQ), 2018). The room air temperature was allowed to vary within the range of 20 – 24.5 °C. Furthermore, the selected temperature range fulfills the design recommendations for operative temperature within offices based on the indoor environmental standard SFS-EN 15251 (2007), class II (20 – 26 °C). Range of the supply air temperature of a ventilation system was set between 16 – 20 °C. The maximum available and the minimum allowed airflow rates with VAV ventilation system were 2 and 0.15 l/s,m^2, respectively. The design and the maximum allowed CO_2 concentration set points were 800 and 1200 ppm (Martin, 2017), respectively, and the maximum allowed airflow rate was used when CO_2 concentration of a room reaches the maximum CO_2 concentration set point (Finnish Society of Indoor Air Quality (FiSIAQ), 2018). The constant design set point for CO_2 concentration (800 ppm) was used in the VAV reference case without demand response control of ventilation airflows. Instead, both of the set points (800 or 1200 ppm) were used in the cases where airflows were controlled by demand response depending on the trend of the district heat and electricity prices. Table 3 summarizes used set points for each demand response control cases.

4. Results and discussion

This chapter presents the simulation results of the case studies. The used marginal value and limiting outdoor temperature for space heating ventilation system in this analysis are ±75 €/MWh and 0 °C. The marginal value was selected by minimizing the heating energy cost of the studied case (Martin, 2017).

Breakdown of energy consumption of two reference cases with CAV and VAV ventilation systems, without demand response control, are presented in Table 4. Results are shown with two different occupancy schemes. In the reference cases, room air temperature set point is 21 °C and supply air temperature is controlled according to the control curve shown in Figure. 5.

Table 4 shows that by changing the control of airflow rate from CAV to VAV, the annual district heat energy and electricity consumption reduce up to 44 and 64%, respectively. The VAV system has substantially lower heating demand of ventilation and electricity consumption of fans, due to the lower airflow rates compared to the CAV case. Increasing the occupancy level slightly decreases the total district heat energy consumption due to the higher internal heat gains.

4.1 Demand response control with the CAV ventilation

4.1.1 Energy and cost

Table 5 shows the effect of the demand response control of space heating and ventilation supply air temperature on annual district heat energy consumption and heat energy cost with the CAV ventilation for different occupancy levels.

The results show that the demand response control of only space heating reduced district heat energy consumption and heating energy cost by around 3 to 5%, respectively, for both occupancy ratios. The demand response control of only supply air temperature had no any benefit; instead, the energy consumption and cost slightly increased. The reason is that the heat output from the radiators increased when the supply air temperature was reduced because room air temperature set point was constantly 21 °C. The saving potentials of district heat consumption and heating energy cost were slightly more when demand response control was simultaneously applied for both space heating and supply air temperature because both the heat output from the radiators and the supply air temperature were increased at the same time. Besides, the district heat energy consumption and heating energy cost can be reduced by around 3 and 6%, respectively, for both occupancy ratios.

4.1.2 Room air temperature

Figure. 7 shows the effect of the demand response control of space heating and supply air temperature on the indoor air temperature of the coldest room (the office room 8 shown in Figure. 3) during the occupied hours (2835 h) with the studied occupancy ratios. Difference between indoor air temperature of the cases with and without demand response (the reference case) is increased as the occupancy ratio increases. With demand response control, the indoor air temperature was lower than the minimum acceptable temperature (20 °C) for less than 2% (56 hours) of the occupied hours. Occupancy did not have effect on the indoor air temperature in the demand response case but the temperature was slightly higher with higher occupancy without demand response control.

4.2 Demand response control with the VAV ventilation

4.2.1 Energy and cost

Table 6 shows the effect of the demand response control of space heating, ventilation supply air temperature and ventilation airflow rates on annual district heat energy and electricity consumption and energy costs with the VAV ventilation.

Table 6 shows that the demand response control of airflows reduces both district heat and electricity consumptions and costs with the studied occupancy ratios. If the demand response control is expanded to space heating as well, the savings in district heating slightly increase and the maximum district heat cost savings are around 11% with both of the occupancy ratios. The supply air temperature control does not bring any additional savings.

4.2.2 Room air temperature and CO_2 concentration

Figure. 8 shows the effect of demand response control and ventilation airflow control mode (CAV/VAV), on the indoor air temperature of the coldest room (the office room 8 shown in Figure. 3) with 40% occupancy ratio. Results of the reference cases show that for more than 55% of the occupied hours (1560 h) the indoor air temperature with the VAV ventilation system is higher than the CAV one, and for the rest hours (1275 h) the differences between these systems are insignificant. The VAV ventilation system provides more wider range of the indoor air temperature than the CAV ventilation system and then requires lower fan speeds, because it uses less energy.

Also, results show that in the VAV cases, only demand response control of space heating had effect on indoor air temperature. In the cases with that control approach, the indoor air temperature was lower than the reference case for almost 70% of the occupied hours (1985 h). Applied demand response control of ventilation supply air temperature or airflow rate had insignificant impact on the room air temperature.

Also, the room air temperature is lower than minimum acceptable indoor temperature (20 °C) for almost 3% of the occupied hours (85 h). Once the demand response control is applied for the CAV and VAV ventilation systems, more than 60% of the occupied hours (1700 h) the indoor air temperature is significantly higher with the VAV ventilation system and the rest hours the differences are negligible.

Figure. 9 shows the influence of the demand response control on the CO_2 concentration of the same room (see Figure. 3, room 8) as used in the indoor air temperature analysis. The CO_2 concentration set point is constant (800 ppm) all the time if ventilation airflows are not controlled by demand response. The studied demand response control algorithm with the used dynamic electricity price increase the CO_2 concentration set point from 800 ppm to 1200 ppm for 89% of the occupied hours (2523 h). In the demand response case, the 1200 ppm CO_2 concentration level is attained only for 0.1% of the occupied hours and about 85% of the time the CO_2 concentration is below 1000 ppm.

The reason for the low number of hours achieving the set point (1200 ppm) is due to the low ventilation need of the case, which results in a low potential of reducing airflows during the demand response control.

For the VAV reference case, shown in Figure. 10, the airflow rate of the same room is below 0.5 $l/(s.m^2)$ for the majority (70%) of the occupied hours because of low occupancy ratio which is sufficient to maintain the CO_2 concentration on the set point level (800 ppm). Hereafter the ventilation demand for the VAV reference case, where demand response was not introduced, is low. Therefore, the airflow demand response control did not have a significant impact on the CO_2 concentration once the minimum allowed airflow rate is 0.15 $l/(s.m^2)$.

The high share of CO_2 set points of 1200 ppm is not a problem for people in the studied building, but with a higher occupancy rate or another building it might cause a continuously high CO_2 concentration during the occupied hours. However, this is not a goal and therefore it would be good to set a time limit for how many hours per day the CO_2 set point can be 1200 ppm. Those hours could be concentrated to the most expensive periods of the day. By this way cost savings could be achieved without continuously high CO_2 concentration.

5. Conclusion

This study examined the influence of demand response control of heating and ventilation on energy costs, thermal conditions and CO_2 concentration in an educational office building heated by district heating. The demand response was used to control space heating, heating of ventilation and ventilation airflow rates. The developed demand response controls were based on hourly district heat and electricity prices, thermal conditions and CO_2 concentration.

The demand response control was applied on the space heating and supply air temperature set points for the constant air volume ventilation system. Also, the demand response control was intended to adjust the space heating set point, supply air temperature set point and airflow rate for the variable air volume ventilation system.

This study showed that the demand response control on the ventilation systems for a building heated by district heating is both cost and energy effective. Also, the indoor air temperature can be well maintained at the acceptable range for both ventilation systems.

The influence of the demand response control on heating energy cost savings was higher with the variable air volume ventilation system than with the constant air volume ventilation.

In the constant air volume ventilation system, the maximum heating energy consumption and cost savings were around 3 and 6 %, respectively. With the variable air volume ventilation system, the maximum savings for heating energy consumption and cost as well as electricity consumption and cost were around 8, 11, 9 and 2 %, respectively. Increasing occupancy ratio in the variable air volume ventilation system increased slightly heating energy and cost savings by the rule-based demand response. It was negligible for the constant air volume system.

Developed demand response control algorithms could be applied to the demand response control of heating and ventilation of office or educational buildings equipped with district heating and balanced CAV or VAV ventilation system.

6. Acknowledgments

This study is part of the "IoT to optimise buildings energy use for sustainable energy systems" (REINO)-project, funded by Business Finland, Fidelix Ltd., Fourdeg Ltd., Granlund Ltd., and SRV Construction Ltd. Authors would also like to thank Aalto University Campus & Real Estate Ltd. for their kind cooperation.

7. Declaration of interest statement

The authors declare no conflict of interest.

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Table 1. Main features of the structures and thermal bridges of the studied building.

Structure	**Description** (mm)	**U-value** (W/(m^2.K))
External wall	Brick: 130	0.38
	Air gap: 20	
	Mineral wool: 100	
	Concrete: 160	
	Render: 10	
Roof	Gravel: 50	0.30
	Mineral wool: 20	
	Polyamidic sheet: 0.2	
	Light-weight concrete: 30	
	Light-gravel: 235	
	Polyamidic sheet: 0.2	
	Concrete: 250	
Internal walls	Concrete: 160 - 260	0.62
Internal floor	Concrete: 150	2.39
Window	3-pane low emissivity windows with argon filling and wooden frames	1.10
Thermal bridges		
Structure part	**Conductance** (W/(m.K))	
External wall / external wall	0.06	
External window[1] perimeter	0.04	
Roof / external wall	0.08	

[1] Solar heat transmittance (g-value) is 0.5.

Table 2. Main characteristics of ventilation system of the 4th floor.

Ventilation system	Description / Value	Comment
Air flow control		VAV, with temperature and CO_2 control, in the meeting room, CAV in the other rooms (control curve of the supply air temperature are shown in Figure. 5)
Operation schedule	00:00-24:00	Fans are continuously full speed in the rooms with CAV control
Supply airflow rate	1.15m^3/s	
Supply fan pressure rise	1013 Pa	At nominal airflow rate
Supply duct static pressure set point	700 Pa	AHU is controlled according the static duct pressure
Supply fan efficiency	67 %	At nominal airflow rate
Exhaust airflow rate	1.15 m^3/s	
Exhaust fan pressure rise	701 Pa	At nominal airflow rate
Exhaust duct static pressure set point	500 Pa	
Exhaust fan efficiency	58 %	At nominal airflow rate
Heat recovery, $\eta^1_{temperature}$	72 %	Temperature efficiency
SFP-value of AHU	2.55 kW/(m^3/s)	At nominal airflow arte

[1] The temperature efficiency was defined according to EN 308 (1997) standard.

Table 3. Summarized set points for demand response controls.

Demand response control on the CAV ventilation system								
Demand response control	Room air temperature (°C)			Supply air temperature of ventilation system (°C)			Specific airflow rate and indoor air CO_2 concentration [(l/s.m^2) / CO_2(ppm)]	
	minimum	normal	maximum	minimum	medium	maximum	minimum	maximum
Space heating	20	21	24.5	16-20 (according to the control curve (see Figure. 5))			2.0 / N.A.	
Supply air	21			17	20	22	2.0 / N.A.	
Airflow	21			16-20 (according to the control curve (see Figure. 5))			2.0 / N.A.	
Demand response control on the VAV ventilation system								
Space heating	20	21	24.5	16-20 (according to the control curve (see Figure. 5))			N.A.	
Supply air	21			17	20	22	N.A.	
Airflow	21			16-20 (according to the control curve (see Figure. 5))			0.15 / 1180[a] 0.15 / 780[b]	2.0 / 1200[a] 2.0 / 800[b]

[a] The values when the price trend is decreasing (CS = -1).

[b] The values when the price trend is increasing or flat (CS = +1 or 0).

Table 4. Energy consumption for the reference cases without demand response control.

Ventilation	Occupancy scheme (%)	District heat. kWh/m^2.a			Electricity. kWh/m^2.a				
		Space heating	AHU heating	Total district heat	Electric cooling	Equipment	HVAC auxiliary	Lighting	Total electricity
CAV	40	69.4	59.2	128.6	1	3.8	38.7	13.9	57.4
	70	66.1	58.7	124.8	1	5.7	38.7	13.9	59.3
VAV	40	64.6	7.4	72	1	3.8	2.2	13.9	20.9
	70	61.4	8.5	69.9	1.1	5.7	2.9	13.9	23.6

Table 5. Influence of demand response control on total district heat energy consumption and cost with the CAV ventilation and two occupancy levels.

Occupancy ratio (%)	Demand response control		Total district heat consumption		District heat energy cost	
	Space heating	Supply air	kWh/m^2	%	€/m^2	%
40	Reference		128.6	0.0	8.2	0.0
	x		125.2	-2.7	7.8	-4.9
		x	129.8	0.9	8.2	0.4
	x	x	125.1	-2.8	7.7	-6.1
70	Reference		124.8	0.0	8.0	0.0
	x		121.4	-2.8	7.6	-5.0
		x	126.0	0.9	8.0	0.4
	x	x	121.2	-2.9	7.5	-6.3

Table 6. Influence of demand response on total district heat energy and electricity consumption and costs with the VAV system and two occupancy levels.

Occupancy ratio (%)	Demand response control			Total district heat		District heat energy cost		Total electricity consumption		Electricity cost	
	Space heating	Supply air	Airflow	kWh/m²	%	€/m²	%	kWh/m²	%	€/m²	%
40	Reference			72	0	4.7	0	20.9	0	5.8	0
	-	-	x	69.8	-3.1	4.5	-4.3	19.6	-6.2	5.7	-1.7
	x	-	x	67.3	-6.5	4.2	-10.6	19.6	-6.2	5.7	-1.7
	x	x	x	67.4	-6.4	4.2	-10.6	19.6	-6.2	5.7	-1.7
70	Reference			69.9	0	4.5	0	23.6	0	6.2	0
	-	-	x	66.8	-4.5	4.3	-4.4	21.5	-8.9	6.1	-1.6
	x	-	x	64.3	-8.1	4.0	-11.1	21.5	-8.9	6.1	-1.6
	x	x	x	64.3	-8.1	4.0	-11.1	21.5	-8.9	6.1	-1.6

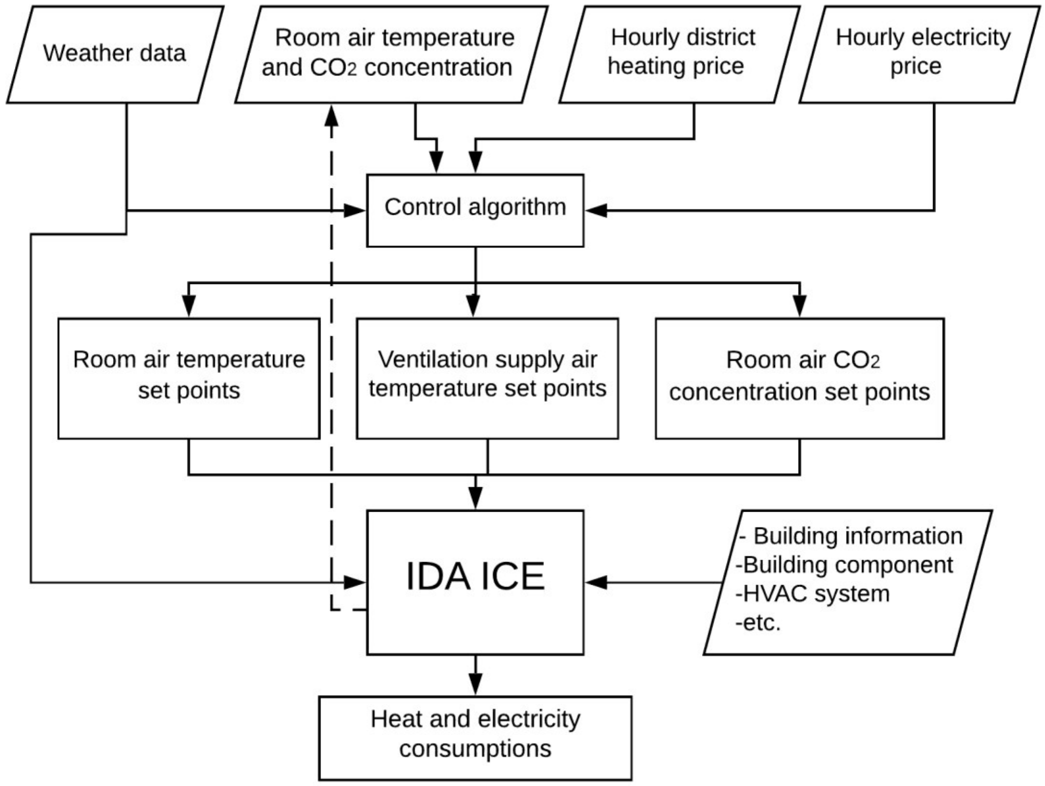

Figure. 1. Principle of simulation process.

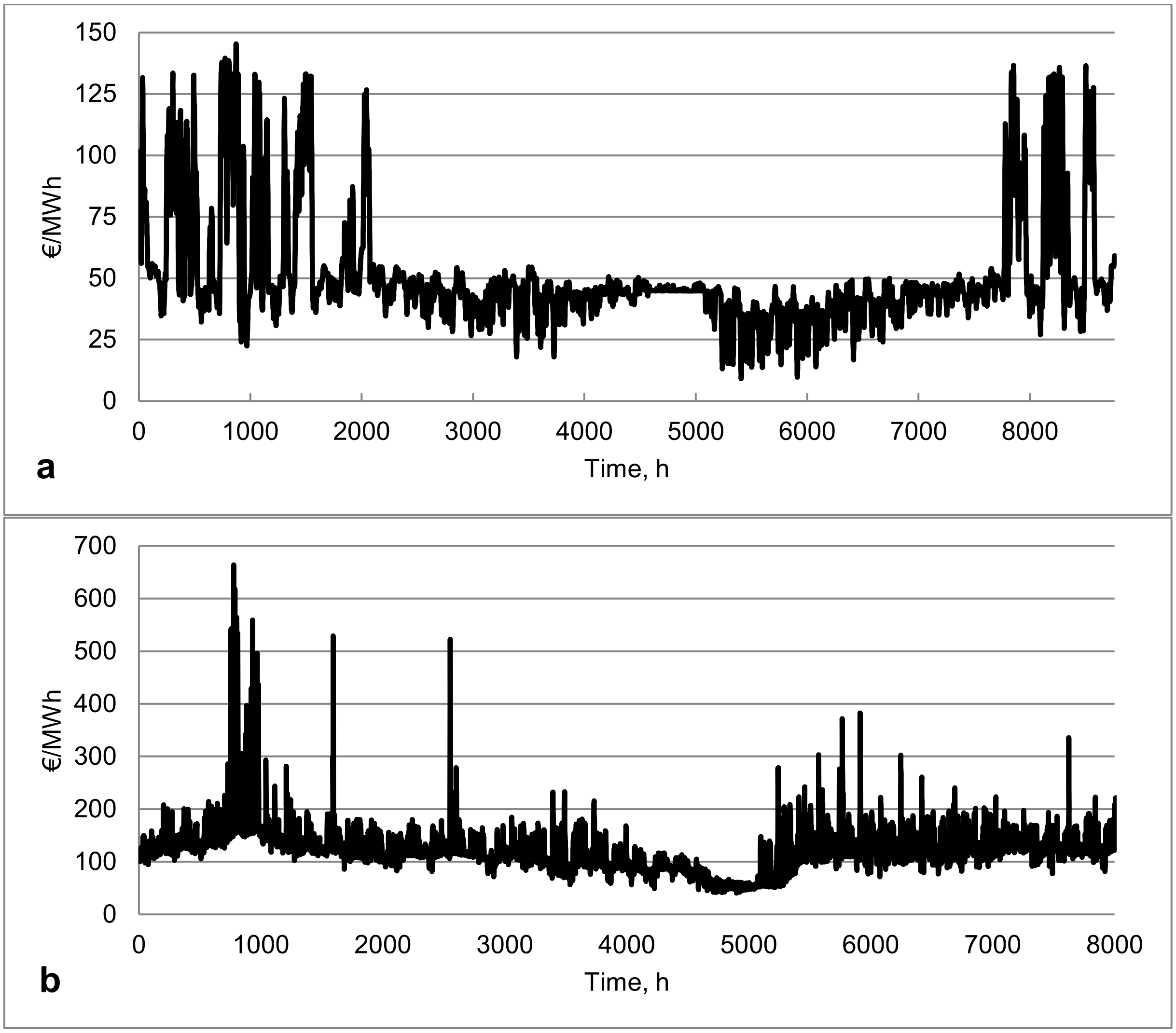

Figure. 2. Hourly district heating price (a) and electricity price used in the study (b).

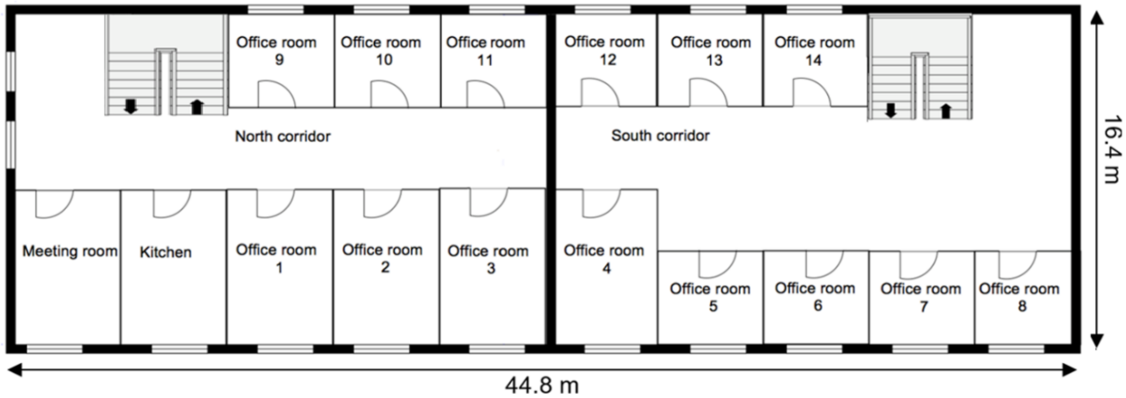

Figure. 3. Layout of Otakaari 4, 4th floor building model.

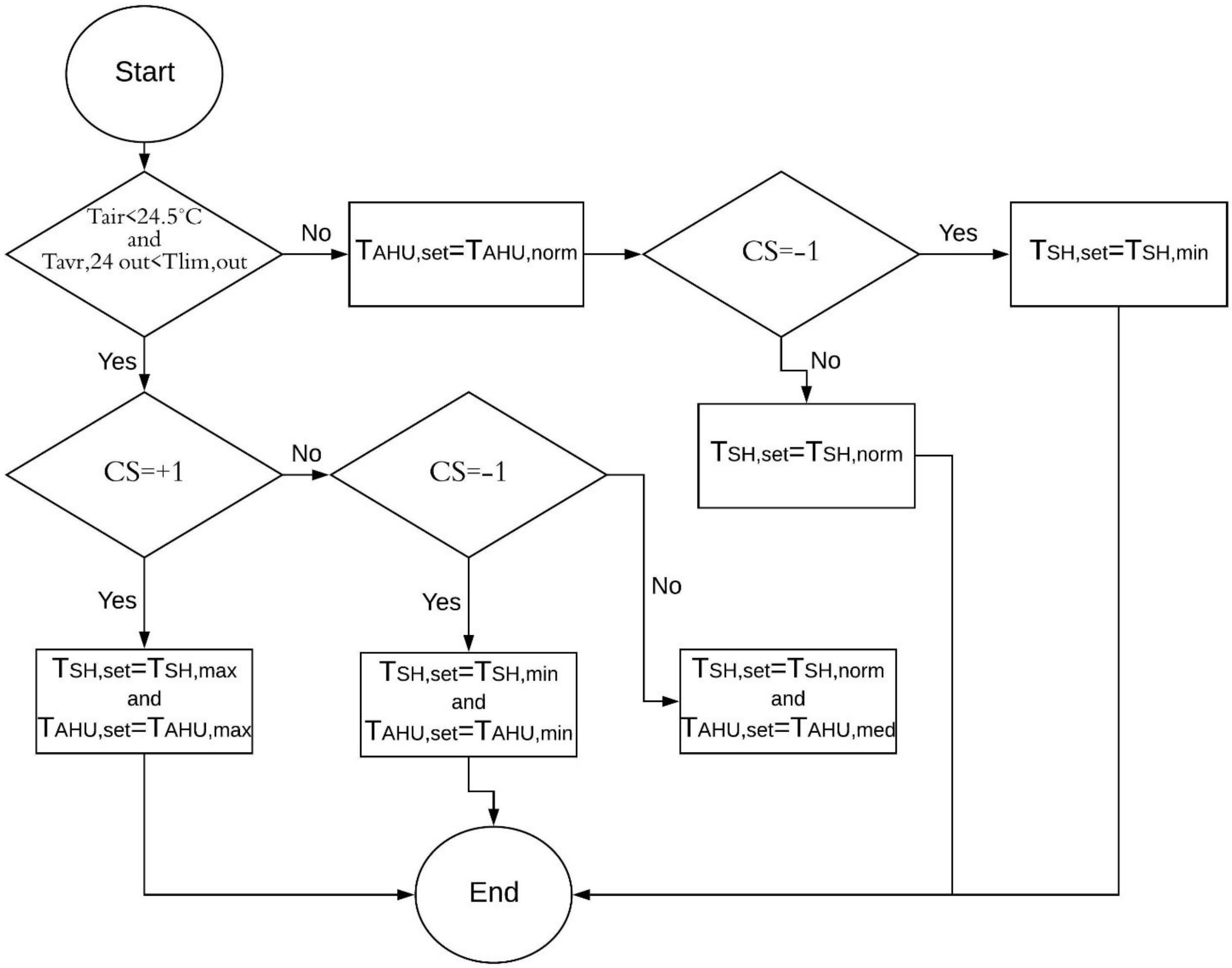

Figure. 4. The flowchart of demand response control with the CAV ventilation system.

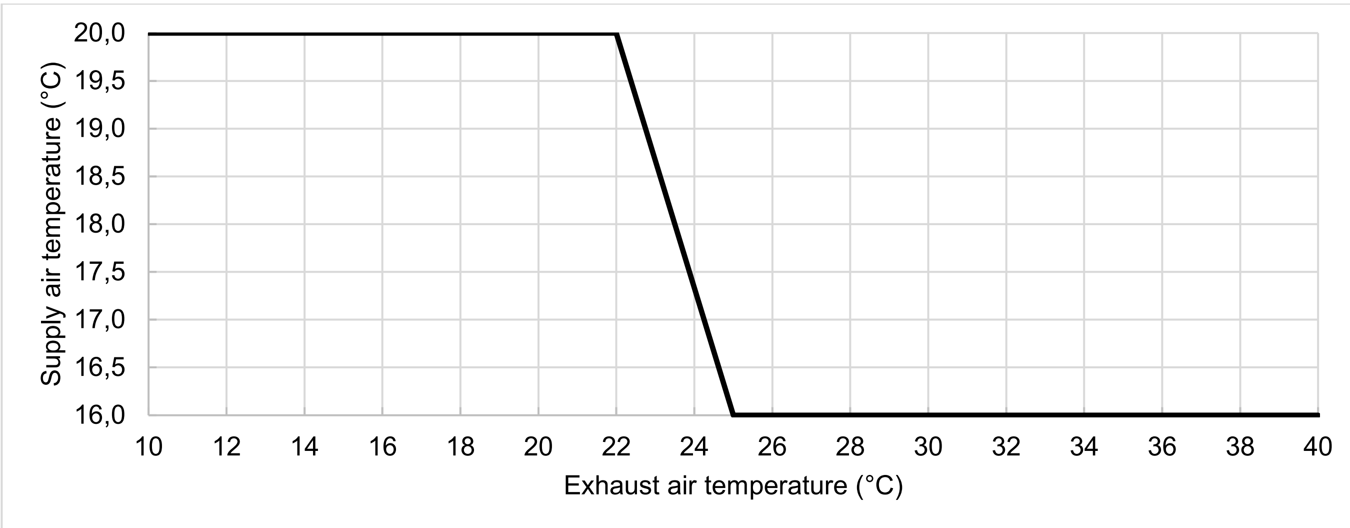

Figure. 5. A control curve of supply air temperature.

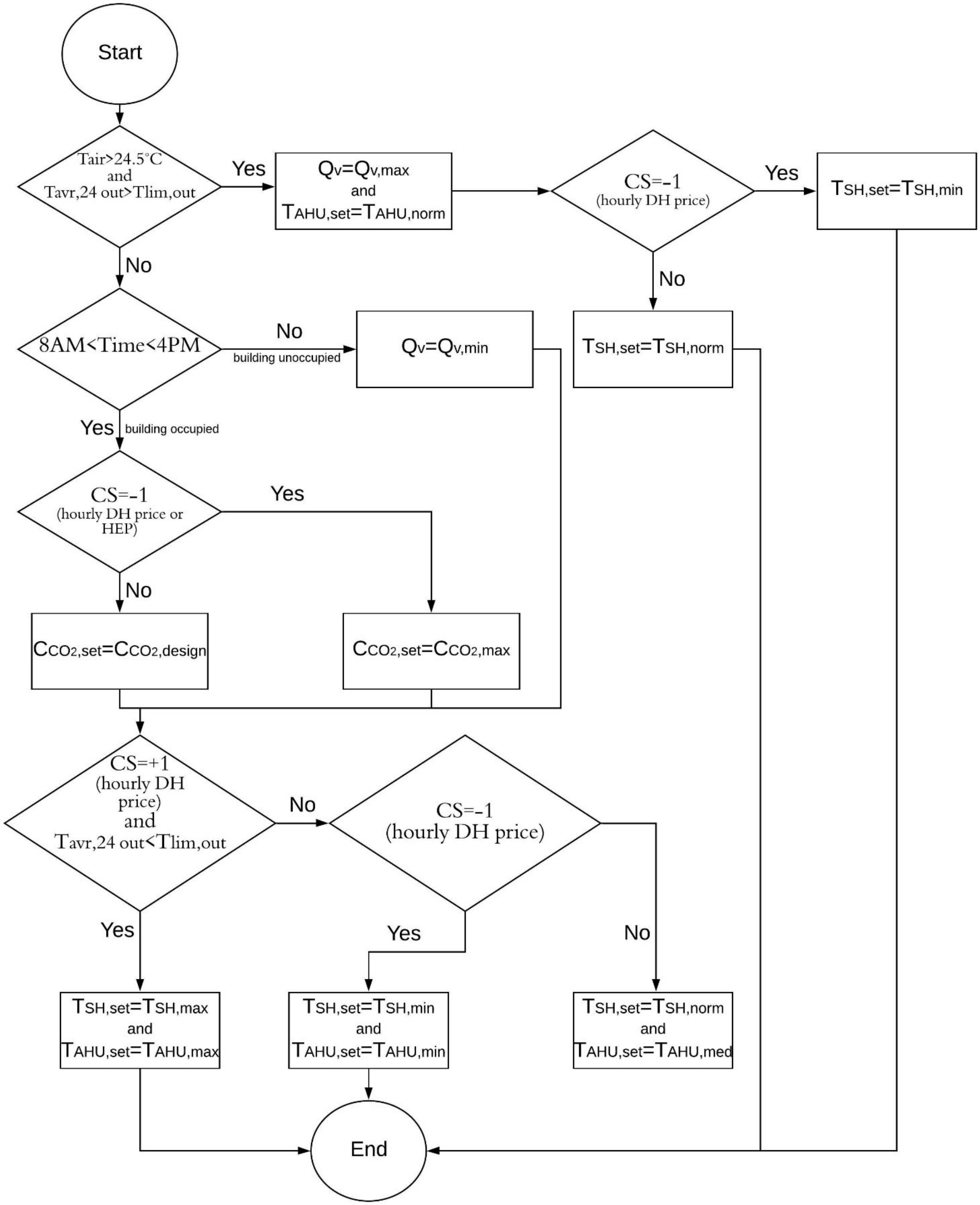

Figure. 6. The flowchart of demand response control with the VAV system.

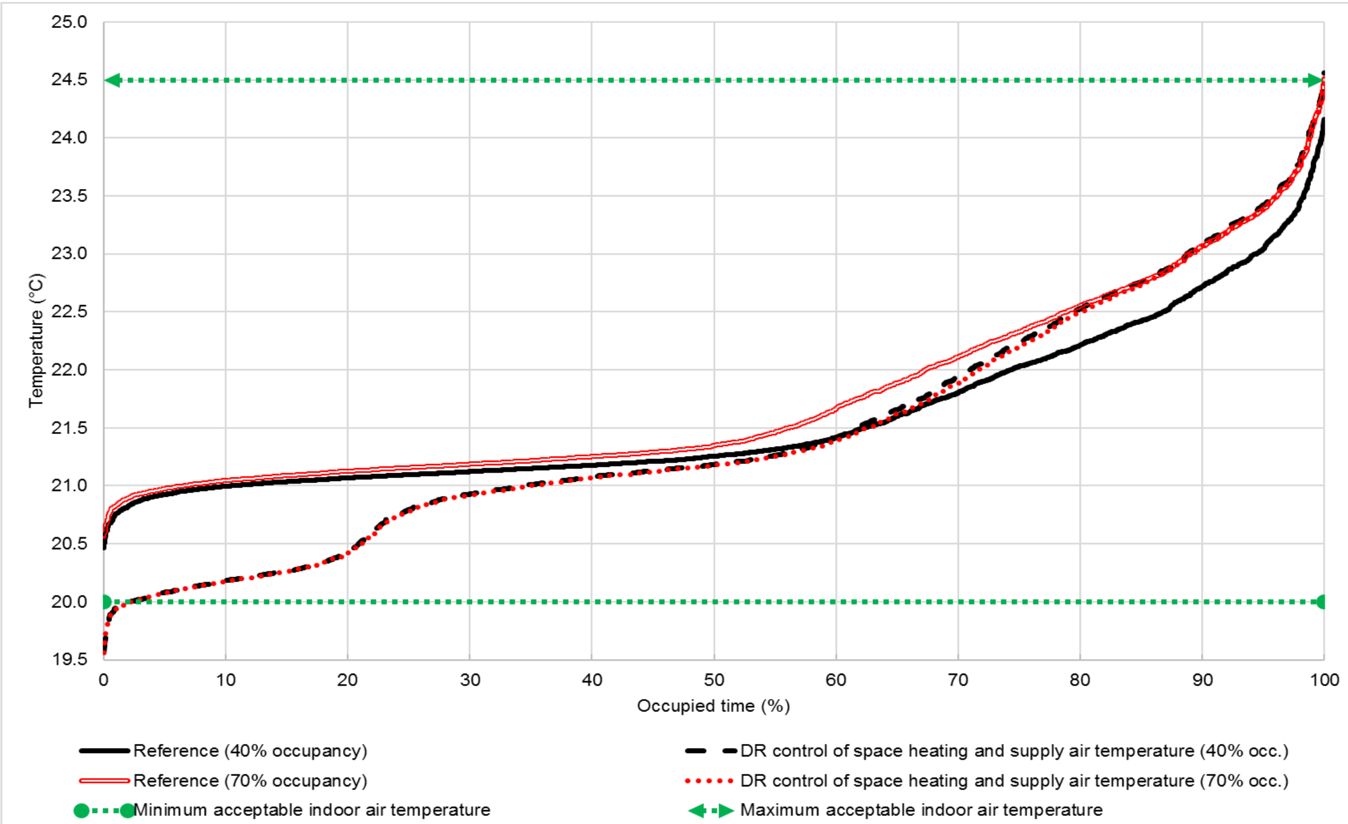

Figure. 7. Indoor air temperature of the coldest room (see Figure. 3, office room 8) during the occupied hours (2835 h) with CAV system for 40 and 70% occupancy (occ) ratios with and without demand response control.

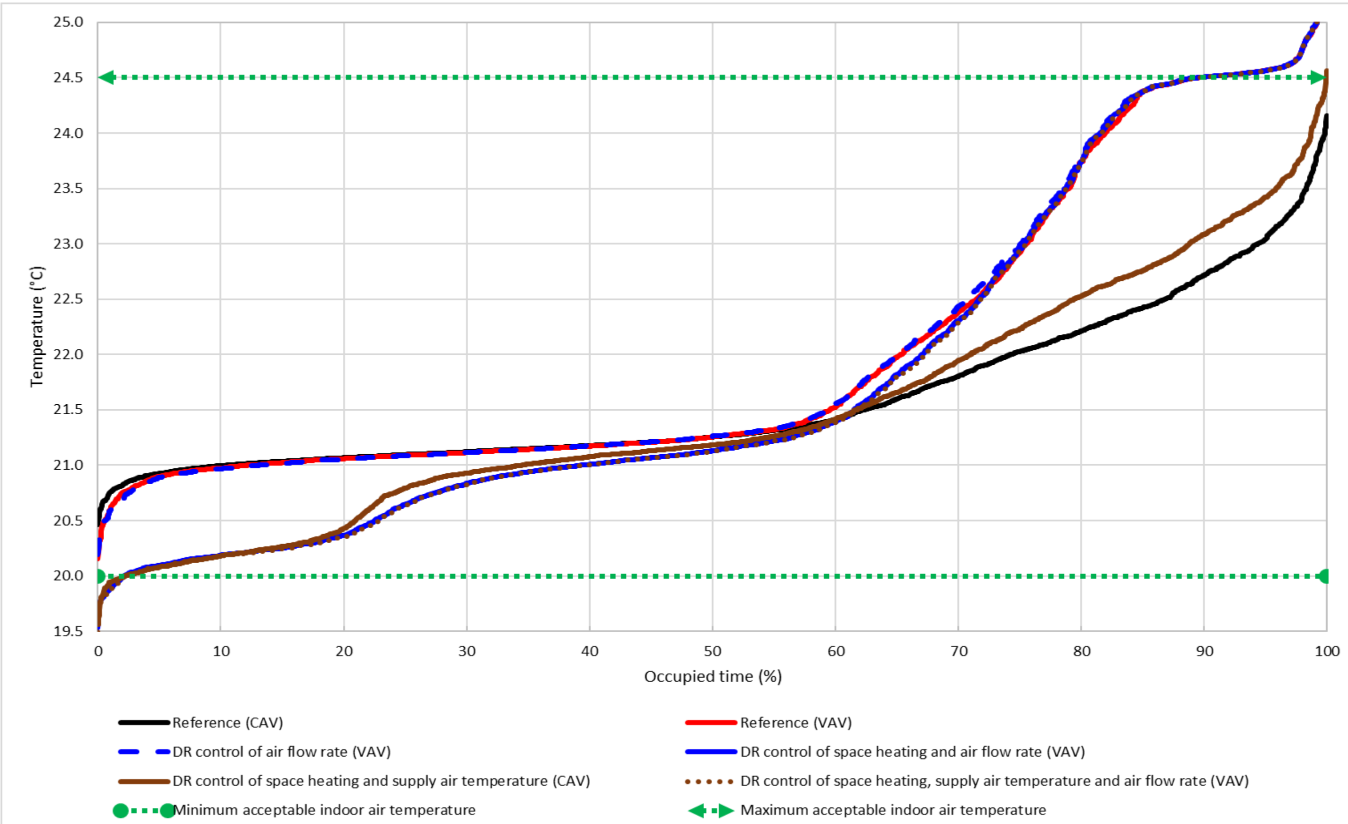

Figure. 8. Indoor air temperature during the occupied hours (2835 h) with CAV and VAV systems and 40% occupancy ratio with and without demand response control for the coldest room.

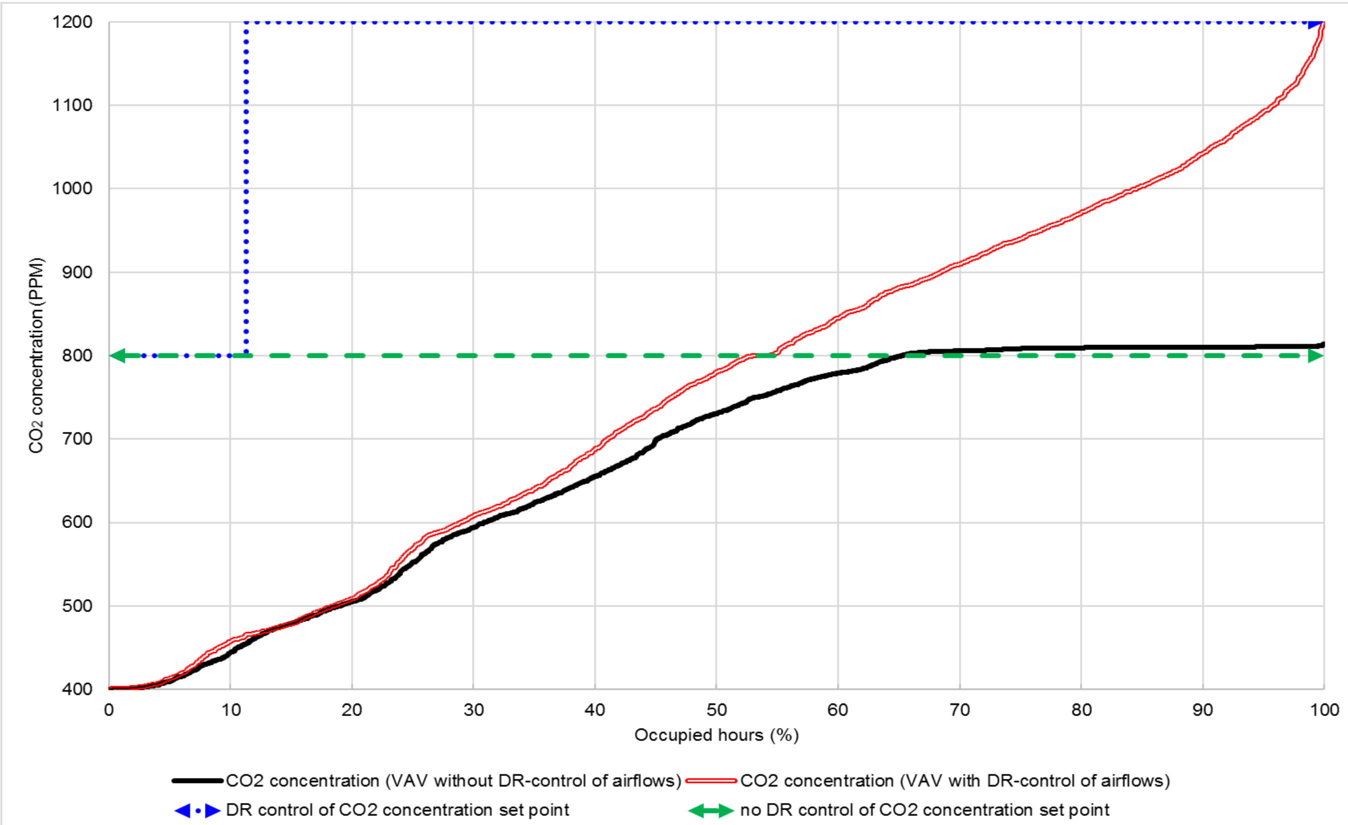

Figure. 9. Influence of the demand response control on the CO_2 concentration of the coldest room during the occupied hours (2835 h) with 40% occupancy level.

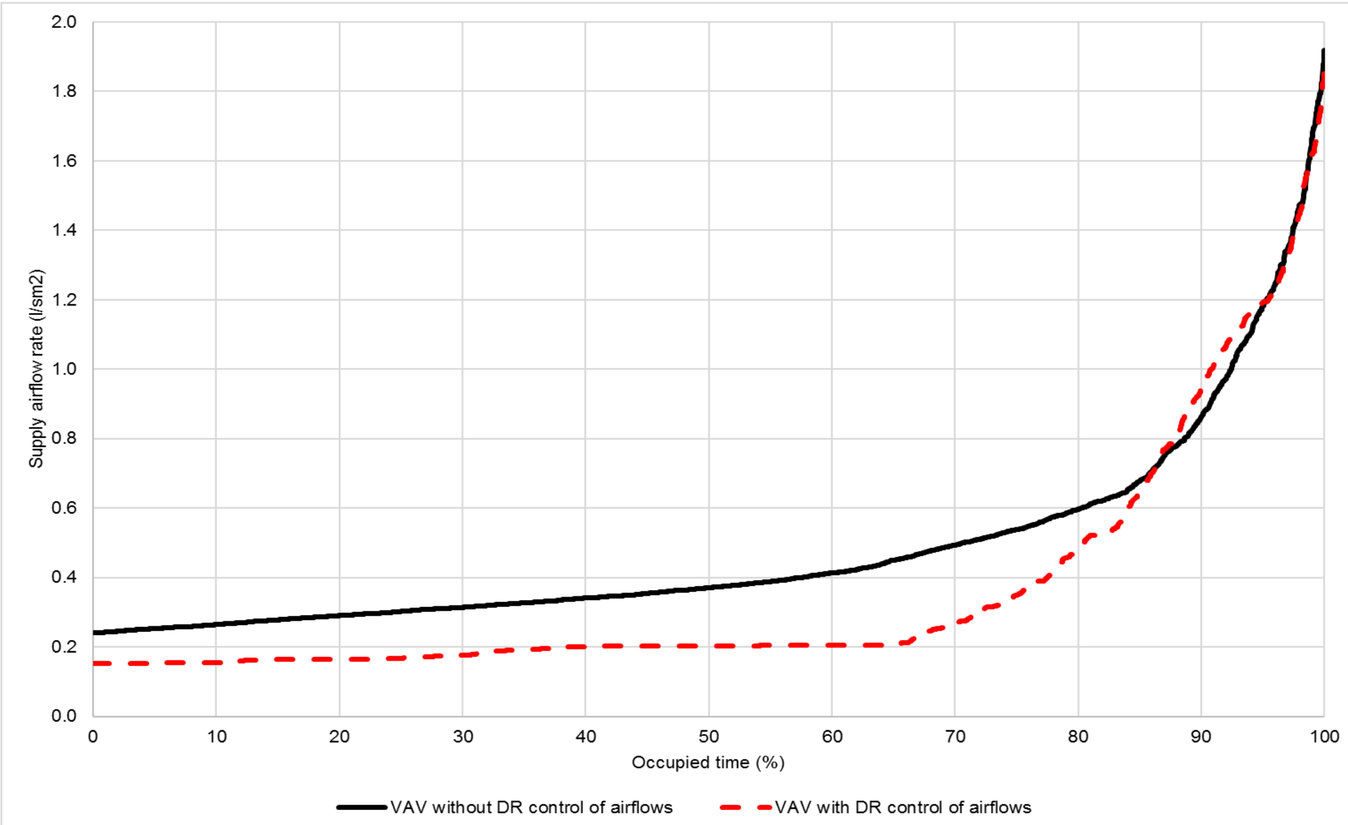

Figure. 10. Duration curve for specific supply airflow rate for the VAV reference case and the airflow demand response control during the occupied hours (2835 h).

Figure. 1. Principle of simulation process.

Figure. 2. Hourly district heating price (a) and electricity price used in the study (b).

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Figure. 4. The flowchart of demand response control with the CAV ventilation system.

Figure. 5. A control curve of supply air temperature.

Figure. 6. The flowchart of demand response control with the VAV system.

Figure. 7. Indoor air temperature of the coldest room (see Figure. 3, office room 8) during the occupied hours (2835 h) with CAV system for 40 and 70% occupancy (occ) ratios with and without demand response control.

Figure. 8. Indoor air temperature during the occupied hours (2835 h) with CAV and VAV systems and 40% occupancy ratio with and without demand response control for the coldest room.

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