Evaluation of energy performance of mechanical ventilation control strategies under different climatic conditions

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Abstract

No clear guidelines are available for operating mechanical ventilation systems with bypass control in order to maintain the indoor environmental quality (IEQ) levels recommended by standards with the minimum possible energy use. This paper used dynamic computer simulations to study the energy and IEQ implications of multiple mechanical ventilation strategies for office buildings under different climatic conditions. Although significant cooling energy savings were achieved by bypassing the heat exchanger during the cooling season, the total primary energy savings only marginally decreased in cold and dry climates. This was due to the fan energy use, which even exceeded the cooling energy savings in hot and humid climates.

Key Innovations

- Bypassing the heat exchanger while increasing the ventilation rate leads to marginal total energy savings.
- Bypass modes lead to higher cooling energy savings in locations where the cooling need is dominant.
- Cooling energy savings could be surpassed by the increase in fan energy use, especially in hot and humid climates.

Practical Implications

In order to determine the implications of the simulated scenarios the limitations of the components used in the simulation software were identified. An appropriate component was selected according to the specifications of the modelled system. The implemented control was verified by introducing intermediary variables in the model.

Introduction

One of the most significant global development challenges for the built environment is the mitigation of the impact of energy-intensive mechanical heating, ventilation and cooling systems (HVACs) in buildings. Growing population around the world and the fact that people tend to spend almost 90% of their time indoors (Olesen & Seelen, 1993), makes indoor environmental quality an important parameter to account for in new and existing buildings. Nowadays, more people rely on mechanical systems to maintain acceptable levels of Indoor Environmental Quality (IEQ). Mixed-mode buildings combine the use of mechanical and passive techniques to maintain thermally comfortable indoor environments. However, there are no clear guidelines on how to operate such mechanical ventilation systems in order to maintain acceptable levels of IEQ with the minimum possible energy use. Dynamic thermal modelling simulations were performed to evaluate the energy and indoor environmental performance of mechanical ventilation systems under different climatic conditions. The objective of this research was to identify the optimum operation mode of the mechanical system: heat recovery, heat recovery with bypass for cooling, or heat recovery with bypass for cooling only outside occupancy to achieve energy savings whilst maintaining acceptable levels of IEQ.

Methods

This paper used dynamic computer simulations developed in IDA ICE (EQUA Simulation AB, 2013) for an office application to examine the performance of different mechanical ventilation strategies under multiple outdoor conditions. The climatic conditions of Edinburgh, Scotland; Copenhagen, Denmark; Zurich, Switzerland; and Palermo, Italy were investigated. The mechanical ventilation was operated in sensible heat recovery mode. Three different scenarios were investigated (Table 1). In the reference scenario, the heat exchanger was always operational. In the other two, the heat recovery unit was bypassed with increased ventilation for cooling purposes either during both day- and night time or only outside occupancy (night time).

In order to compare and analyse the results, the following key performance indicators (KPIs) were used: yearly room temperature and humidity distribution, yearly CO\textsubscript{2} concentration distribution as an indicator of indoor air quality (IAQ), and energy use.
Building model

A building module consisting of two 19.8 m² office spaces with opposite orientations, South and North, connected by an 8.6 m² corridor were modelled as described by Olesen & Dossi (2004). All spaces had a height of 2.8 m.

The module (Figure 1) was part of a multi-storey office building with identical spaces around it. Thus, each office had only one external wall (10 m²) either South or North according to its orientation. The heat transmission through the internal walls, floor, and ceiling of building module was ignored since similar conditions were assumed in the adjacent modules. The building construction had a thermal mass of 14 kJ/m²·K. The building envelope (Table 2), infiltration, internal heat gains, and external blind control were based on Kolarik et al. (2011) and Spitzer (2014). Infiltration was set to a constant value of 0.2 air changes per hour (ACH) through the external area of the module and was included in the total required air flow rate.

![Figure 1. Building module layout. Adapted after (Olesen & Dossi, 2004).](image)

The total internal heat load of each office (35.7 W/m²) consisted of two occupants (in total 11.8 W/m², each with a metabolic rate of 1.1 met), two computers and one printer (in total 12 W/m²) with a long-wave radiation fraction of 50%, and lighting (11.9 W/m²) with a convective fraction of 0.5 (ASHRAE, 2013). The corridor was only fitted with lighting of 7.1 W/m² (ASHRAE, 2013), also with a convective fraction of 0.5. All internal heat gains were active on weekdays from 9:00 to 12:00 and 13:00 to 16:00 (CEN, 2019).

Each external wall had a 4.95 m² window (3 pane glazing with a wooden frame) positioned at a height of 0.75 m and 0.3 m from the side walls. The window properties were: solar transmittance 0.6, glazing heat transfer coefficient 1.9 W/(m²·K), solar heat gain coefficient 0.7, and heat transfer coefficient 2.1 W/(m²·K). For an incident solar radiation higher than 100 W/m² on the outside of the glazing, an external blind shaded the upper part of the window (2.7 m²). The shading strategy did not change the windows’ U-value. However, the visual transmittance and the solar gain factor were reduced by 9% and 14%, respectively.

Air flow rate

Ventilation was supplied to all spaces with a constant air volume (CAV). In all scenarios the aim was to achieve a Category II IAQ according to EN16798-1:2019 (CEN, 2019), which corresponds to an expected dissatisfaction of 20% of total occupants. Thus, the required air flow rate in each office during occupancy, 1.06 L/(s·m²), was determined according to Method 1: Method based on perceived air quality from the EN16798-1:2019 standard (CEN, 2019). According to EN16798-1:2019, the total ventilation rate ($q_{tot}$ in L/s) for the breathing zone is:

$$q_{tot} = n \cdot q_p + A_p \cdot q_b$$

(1)

where $n$ is the design value for the number of persons in the room, $q_p$ is the ventilation rate for occupancy per person in L/(s·person), $A_p$ is the floor area in m², and $q_b$ is the ventilation rate for emissions from building in L/(s·m²).

For the ventilation rate for occupancy per person, $q_p$, the Category II value for non-adapted persons was used (7 L/(s·person)) (CEN, 2019). The majority of building materials were considered to have a very low emission of
pollutants. Therefore, $q_h$ equal to 0.35 L/(s·m²) was selected for a Category II very low polluting building (CEN, 2019).

When the heat recovery unit was bypassed and ventilation was increased for cooling purposes, the air flow rate was increased to 1.51 L/(s·m²), Category I IAQ (CEN, 2019). As recommended by EN16798-1:2019, one air change was delivered within 2 hours prior to occupancy to each office (CEN, 2019). An air flow rate of 0.15 L/(s·m²), the minimum recommended air flow rate for diluting building emissions, was continuously supplied in the corridor connecting the two offices.

**Air handling unit model**

Air was supplied to the spaces through a compact cross-flow air-to-air heat recovery unit (Figure 2). The ideal cross-flow heat exchanger model used in IDA ICE (EQUA Simulation AB, 2013) could not transfer humidity between the two air flows. Nevertheless, excess humidity could be removed by the heat exchanger if condensation occurred in the unit. In order to obtain realistic information, the heat exchanger (HEX) model was dimensioned according to a product available on the market (Mitsubishi Electric Corporation, 2017).

![Figure 2. Air handling unit model (HEX: Heat exchanger).](Image)

The heat exchanger had a capacity of 250 m³/h. An external pressure drop of 48 Pa was assumed from the ducting system (40 m duct with a 0.15 m diameter). Using the total required air flow rate (128 m³/h), a specific fan power (SFP) of 0.63 W/(L/s) and sensible heat exchange efficiency of 82% were determined according to the datasheet. No heating and cooling coils were present in the AHU. Therefore, the total energy use for supplying air into the building module was dependent only on the pressure rise over the heat exchanger and the ducting system (48 Pa).

**Heating and cooling system**

Since the focus was the effect of the air handling unit, the specific characteristics (e.g. radiator, radiant system, fan coil) of the heating and cooling solutions were not defined. Thus, the amount of energy needed to condition the thermal environment of the office spaces was estimated using ideal heating and cooling models.

The ideal heater and cooler operated from 09:00 to 16:00 and were dimensioned to cover the heating and cooling needs. Their operation was based on the simplified running mean temperature ($T_{rm}$), a weighted average of the daily mean outdoor temperature of the previous 7 days (CEN, 2019). The heating and cooling setpoints were defined according to the Category II operative temperature limits recommended by EN16798-1:2019, 20 °C for heating and 26 °C for cooling.

Both heating and cooling were available for a running mean temperature between 10 and 15 °C (transitioning periods). Only heating was available for a running mean temperature below or equal to 10 °C (heating season), while only cooling was available when the running mean temperature was above or equal to 15 °C (cooling season).

**Ventilation system control**

Air was supplied to the office spaces through the heat recovery unit at a constant air volume, 1.06 L/(s·m²), on weekdays from 09:00 to 16:00 in all scenarios. For simplification purposes, the supply air temperature setpoint of the AHU was 16 °C. If the outdoor air was lower than the supply temperature setpoint, heat was recovered from the extract air if possible. Cooling took place if the outdoor air was higher than the setpoint and the extract air was lower than the outside air.

An additional control was implemented in scenarios BPC and BPNC where the heat recovery unit was bypassed with increased ventilation (1.51 L/(s·m²) for each office) for cooling purposes. This control was dependent on the scenario, active all day (BPC) or only outside occupancy (BPNC). Moreover, the heat recovery unit was bypassed with increased ventilation only if the following conditions were true:

\[ T_{rm} \geq 15 \text{ °C} \]  
\[ 23 \text{ °C} \leq T_{op} < 26 \text{ °C} \]  
\[ T_{op,max} > T_{out} \]

where $T_{op}$ is the operative temperature, $T_{out}$ is the outdoor temperature, and $T_{op,max}$ is the maximum operative temperature between the two offices, South and North, all in °C. However, as in the other scenarios, the ideal cooler ensured that the operative temperature in the spaces did not increase over 26 °C during occupancy even when the heat exchanger was bypassed.

**Results**

**Outdoor environment**

The IWEC2 data for Edinburgh, Scotland; Copenhagen, Denmark; Zürich, Switzerland; and Palermo, Italy were used in the simulations (ASHRAE, ASHRAE IWEC Weather Files, 2013). The daily mean outdoor temperature and humidity level are shown in Figure 3 and Figure 4, respectively.

According to the Köppen-Geiger classification (Köppen & Geiger, 1930), Edinburgh and Copenhagen are categorized as having an oceanic climate (Cfb) while the climate in Zürich is dominated by a warm humid continental climate (Dfb) with oceanic climate (Cfb) influences. The climate similarity between Edinburgh, Copenhagen, and Zürich are also visible in the outdoor temperature and absolute humidity data. Nevertheless, higher temperatures were observed during the heating and transitioning periods and colder temperatures during the cooling season in the data for Edinburgh compared to Copenhagen and Zürich. Moreover, out of the three aforementioned cities, higher temperatures were registered in Zürich during the cooling season. On the
other hand, the highest temperatures and absolute humidity levels were observed in Palermo, which has a Hot-summer Mediterranean climate (Köppen & Geiger, 1930).

Energy use

Figure 5 shows the primary energy use over the investigated year for heating, cooling, and ventilation (fan energy). The results are grouped by city according to each scenario investigated. The primary energy factors used were 1.9 for electricity and 1 for heating according to (Danish Ministry of Transport, Building and Housing, 2020).

As expected, the additional control (scenarios BPC and BPNC) had no influence over the primary energy use for heating. However, both heating and cooling energy use were influenced by the climate. Since Copenhagen had the coldest climate, it led to the highest primary energy use for heating. As Edinburgh registered higher temperatures during the heating season and transitioning periods and lower temperatures during the cooling season compared to Copenhagen, the primary energy use for both heating and cooling reduced. Due to the higher overall outdoor temperatures during the cooling period a lower heating energy use and an increase in the cooling energy were registered in Zürich compared to Copenhagen. On the other hand, as the highest temperatures were registered in Palermo over the entire year, the building module required the lowest primary energy use for heating and the highest cooling energy use.

Energy savings were however registered when cooling because of the implemented control. In all locations, the cooling energy decreased more when the control strategy was extended over the entire day (BPC) than only outside occupancy (BPNC). Cooling energy savings of 50% and 63% were achieved in Copenhagen for an increased ventilation rate when bypassing the HEX outside occupancy (BPNC) and all day (BPC), respectively. The least cooling energy savings relative to the reference case (REF), 18% (BPNC) and 24% (BPC), were registered in Palermo. Nonetheless, this led to the most absolute cooling energy savings over the entire year out of all the investigated climates, 4.8 and 6.3 kWh/(m²·year), respectively. In Zürich the cooling energy decreased by up to 55%, while in Edinburgh by a maximum of 46%. Overall the least absolute cooling energy savings were possible in Edinburgh with approximately 0.9-1.2 kWh/(m²·year) when increasing the ventilation rate while bypassing the heat exchanger.

Although the cooling energy was greatly reduced, especially in hotter climates, the implemented controls had little impact on the total primary energy use as the fan energy increased. Therefore, in Copenhagen, Edinburgh, and Zürich, the total energy use reduced by only 3% to 7%, with little to no difference between the BPC and BPNC scenarios. In Palermo, total energy savings of 4% were registered when increasing the ventilation rate only outside occupancy (BPNC). However, the total primary energy use reduced by only 1% in the BPC scenario.
Indoor air quality

Figure 6 shows the absolute CO₂ concentration distribution (including 400 ppm outdoor CO₂ concentration). Only the CO₂ concentration distribution for the South oriented office is given in the figure since the air flow rate supplied to the offices was equal.

The CO₂ concentration was always lower than the design limits (Category II EN16798-1:2019) for all scenarios analysed. Moreover, no difference was observed between the reference and BPNC scenarios as ventilation was only increased outside occupancy in the latter.

The increased flow rate during occupancy further improved the IAQ. As the ventilation rate increased also during occupancy (BPC) when cooling by bypassing the HEX was possible, the CO₂ concentration decreased compared to the reference scenario. The decrease was proportional with the amount of time when bypass was possible. Therefore, the biggest decrease in CO₂ concentration was registered in Palermo compared to the other locations as the cooling season ($T_{rm}$ ≥ 15 °C) and bypass operation was the longest.

In Zürich the CO₂ concentration was overall higher compared to the other cities analysed. This was because although the CO₂ generated by the occupants remained constant, the amount of air decreased due to the higher altitude.

Relative humidity

Figure 7 shows the relative humidity (RH) during the investigated year. It can be seen that in Copenhagen, Edinburgh, and Zürich the air was mostly dry (more than
75% data below 50% RH). This occurred mostly during the heating season, when cold air with low humidity levels was heated up to the desired setpoint without humidification. On the other hand, since Palermo registered higher absolute humidity levels during the heating season, the percentage of time below the Category II limit of EN16798-1:2019, 25 %, was lower than for the other locations. In Copenhagen, Zürich, and Edinburgh, the RH rarely exceeded values above the Category II limit, 60% (CEN, 2019). However, as Palermo had higher absolute humidity levels during the cooling season, the RH reached values above 60% for approximately 25% of the time.

Condensation occurred in the HEX model whenever the heat transfer surface reached a temperature below the air’s dew point temperature. However, slightly higher RH levels were registered in the BPC and BPNC scenarios compared to the reference one (REF) for the same location (Figure 7). This was due to the additional control implemented (BPC and BPNC), which bypassed the HEX whenever cooling directly with outside air was possible. Thus, in those instances, the supply air was no longer conditioned by the HEX and the water in the supply air could no longer condensate before entering the office spaces. As the temperature in the indoor space was maintained constant across scenarios, the RH increased in the BPC and BPNC scenarios. Moreover, as the ventilation rate increased when bypassing the HEX for cooling purposes (BPC and BPNC), additional humid air was ventilated into the space. This is particularly visible for Palermo, Italy where humidity levels up to 75% and 80% were registered in the BPC and BPNC scenarios, respectively, values higher than the limits recommended by EN16798-1:2019.

**Indoor thermal environment**

For the analysis of the indoor thermal environment, the operative temperature ranges for hourly calculation of cooling and heating energy from the EN16798-1:2019 standard were used. As the targeted indoor thermal environment was Category II for office buildings, an operative temperature range from 20 °C to 24 °C was defined for the heating season ($T_{op} \leq 10$ °C), and a range between 23 °C and 26 °C for the cooling season ($T_{op} \geq 15$ °C). Since no temperature ranges are defined in the standard for the transitioning periods (10 °C < $T_{rm} < 15$ °C), the lower bound for the heating season, 20 °C, and upper bound for the cooling season, 26 °C were used as limits. Table 3 shows the percentage of occupied time when the indoor thermal environment was within the selected limits. It can be seen that the percentage of occupied time when the operative temperature was within the limits was within a close range (96% and 99%) across the investigated scenarios. Variations occurred between
scenarios due to office orientation, controller deadband, and the selected control signals. However, these variations were not significant as seen in the detail for Palermo, Italy (Figure 8) which made the results comparable.

Table 3. Percentage of time within Category II, EN16798-1:2019 by scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Office</th>
<th>CPH [%]</th>
<th>EDI [%]</th>
<th>PMO [%]</th>
<th>ZH [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>South</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>99</td>
<td>98</td>
<td>96</td>
<td>98</td>
</tr>
<tr>
<td>BPC</td>
<td>South</td>
<td>98</td>
<td>99</td>
<td>99</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>North</td>
<td>98</td>
<td>98</td>
<td>96</td>
<td>98</td>
</tr>
<tr>
<td>BPNC</td>
<td>South</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
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<tr>
<td></td>
<td>North</td>
<td>99</td>
<td>98</td>
<td>97</td>
<td>98</td>
</tr>
</tbody>
</table>

Since the two offices had different orientations, the incident solar radiation was also different on the window surface. Combined with the solar shading strategy, different solar heat gains were registered in the two offices. As the defined operative temperature setpoints had the same values as the indoor thermal environment limits, the operative temperature could vary proportionally to the controller deadband until the ideal heater and cooler reacted to the temperature variation. Therefore, although limited in duration, slightly lower or higher temperatures (±0.2 K) than the selected limits were registered. Moreover, the maximum operative temperature between the two offices ($T_{op,max}$) was used as a control signal for the increased ventilation when bypassing (BPC and BPNC). Therefore, when active, ventilation was increased in the two offices for the same amount of time. This led to instances when more cooling was provided than needed to one of the offices.

Discussion

The results of this study showed that by bypassing the heat exchanger while increasing the ventilation rate did not significantly decrease the total primary energy. This was due to an increase in the energy used for ventilating the spaces. Moreover, in hot and humid climates such as Palermo, the total primary energy savings were not significant when a higher ventilation rate was active over extended periods of time (scenario BPC, 1% decrease) as the fan used more energy when transporting humid air. Nevertheless, as part of the cooling load was covered by the incoming outdoor air when bypassing the heat exchanger (scenarios BPC and BPNC), less cooling was provided by the indoor units. Thus, the cooling energy could be reduced by 18% to 63% compared to the reference case (no bypass) depending on the climatic conditions. This led to higher absolute energy savings in hot and humid than cold and dry climates.

The indoor thermal environment was within the recommended limits for more than 96% of the occupied time and within a close range across the investigated scenarios. Nevertheless, because of the implemented control signal and temperature setpoints chosen, it varied according to climate and scenario. Therefore, the indoor thermal environment could have been further optimised. By selecting independent indicators for the ventilation control of the two office spaces, increased ventilation rates would have been supplied according to the needs of each space. Therefore, fan energy could have been further reduced. Furthermore, by integrating the controller deadband in the cooling and heating setpoints, marginally higher or lower temperatures compared to the recommended limit would have been eliminated at little energy expense.

In this study, the pressure drop was constant over the simulated scenarios. Thus, the fan energy was only dependent on the operation time of the fan and the airflow rate. However, in reality the pressure drop will increase for a higher airflow, which in turn could lead to an increase in the total energy use even for cold and dry climates. At the same time, a lower static pressure could be achieved when bypassing the heat recovery unit (Kyungjoo, Dongwoo, & Taeyeon, 2020). Thus, in order to achieve significant energy savings, the system and control must be further optimised.

Secondly, the ideal heat exchanger available in the simulation software could not transfer humidity between the two air streams. Thus, only the sensible heat exchange efficiency could be given as a parameter. Nevertheless, higher energy savings could be achieved due to the enthalpy recovery. Furthermore, transferring humidity between the two air streams could also provide control over the humidity levels inside the space. Thus, in order to

Figure 8. Operative temperature detail in the south and north offices in Palermo, Italy over the entire year.
to identify the optimum operation mode of the mechanical system with enthalpy recovery, the cooling energy savings must be weighed against the benefits of humidity control over the indoor space.

**Future studies**

This paper provides an insight on the operation of mechanical ventilation systems towards the goal: energy savings without compromising on IEQ. However, the results are limited by the assumed conditions. Thus, in order to identify the optimum operation mode, different building types (e.g. residential, schools, hospitals) with higher volumes and different heat gain levels must be analysed. Moreover, a sensitivity analysis on the pressure drop and ventilation rate should follow with a comparison to natural ventilation strategies based on window opening.

By modelling the humidity transfer between the two air streams in the heat exchanger unit, the energy savings implications on mechanical ventilation and the IEQ throughout and post the COVID-19 era for different units can be studied. Moreover, specific heating and cooling systems (e.g. radiant heating versus air-based systems) must be included in the model to obtain results on a wide range of scenarios.

In order to ensure the validity of the results, the model must be compared to experimental and field data. This can be done by obtaining accurate measurements on the HEX unit (e.g. supply and return temperatures, humidity ratio, and pressure drop) and the conditioned space (e.g. air temperature, CO₂, relative humidity) and comparing the values with the simulation results. Then, by tweaking the parameters of the model, an accurate representation of the unit can be obtained.

**Conclusion**

Bypassing the heat exchanger while increasing the ventilation rate led to marginal reductions in the total primary energy, between 1% to 7%. Moreover, little difference was observed in the energy use between night only and all day bypass in cold and dry climates. Significant cooling energy savings were achieved with the implemented controls whilst maintaining an acceptable indoor thermal environment. The bypass modes led to higher cooling energy savings in locations where the cooling need was higher. However, the cooling energy savings could be surpassed by the increase in fan energy use, especially in hot and humid climates. In order to achieve significant energy savings, the system and the control must be further optimised. All scenarios analysed in this study reached acceptable CO₂ concentrations during occupied hours.

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**References**


