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Detailed assessment of hybrid ventilation control system in a mixed-mode building in cold climate

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Abstract. This paper investigates a hybrid ventilation control method for a mixed-mode office landscape in a cold climate, i.e. Norway. The mixed-mode building utilizes a hybrid ventilation system that combines natural ventilation through automatic window opening with a balanced mechanical ventilation system controlled by demand control ventilation (DCV) method. For natural ventilation, the windows consist of two parts: the upper part which is openable and the lower part that is not openable and equipped with external solar shading. From a control point of view, the article elaborates a control algorithm for the proposed hybrid ventilation based on various parameters including outdoor air temperature, indoor air temperature, indoor CO_2 level, maximum air change per hour (ACH), operation schedules, and heating/cooling setpoints. The simulation results obtained from the hybrid ventilation and mechanical ventilation cases are compared based on thermal comfort, indoor air quality (IAQ), and energy savings. The primary results show that the proposed hybrid ventilation control method can satisfy the thermal comfort and IAQ requirements while reducing the energy use for fan and ventilation cooling by approximately 25% and increasing the space and ventilation heating energy use by only about 4%.

1. Introduction

The building sector in Europe is responsible for a substantial portion of the primary total energy use and greenhouse gas emissions, amounting to 39% and 36%, respectively [1]. This is mainly due to the extensive use of heating, ventilation, and air-conditioning (HVAC) systems, which have become significantly prevalent with the growth of building construction and the improvement in living standards. Improving the energy efficiency of HVAC systems in buildings is crucial to minimize energy consumption and mitigate greenhouse gas emissions, given that individuals spend almost 90% of their time indoors. There is not a one-to-one relationship between the global warming potential (GWP) of equivalent CO_2 (CO_2-eq) invested in a measure, and the CO_2-eq of energy savings, as the time of emission is important when evaluating the net present GWP of a measure. It is therefore important to reduce both the CO_2-eq investments in buildings and the running energy need [2]. A feasible approach to achieve this is the utilization of mixed-mode buildings combining natural ventilation with mechanical systems to deliver eco-friendly ventilation and cooling. This approach offers the potential to reduce reliance on mechanical systems while ensuring optimal comfort levels for building occupants. By leveraging natural ventilation, energy use for cooling can be reduced by approximately 8% to 78%, depending on local weather conditions and air quality [3].

However, achieving effective control of hybrid HVAC systems can be a challenging and controversial task due to the complexity and the impact of indoor and outdoor airflows. Although such systems present an encouraging solution to improve the energy efficiency of buildings and maintain the thermal comfort of occupants, their operation is susceptible to various disturbances, which can compromise their performance. As a result, further research is necessary to develop robust control strategies that can effectively manage the hybrid HVAC system's interactions with the surrounding environment and meet the occupants' comfort requirements.

2. Related studies

Several literature reviews have been conducted to investigate the efficiency of natural and hybrid ventilation approaches in diverse types of buildings. Saber et al. [4] reviewed various control strategies of natural ventilation for buildings in UK and countries with similar climatic conditions. Their findings showed that there is potential to enhance the performance of natural ventilation, especially in industrial buildings. Furthermore, an advanced control strategy such as intelligent control systems (fuzzy logic control) coupled with optimization engine of neural network could be an effective control system for such a design. Hamdy and Mauro [5] proposed three different hybrid control strategies taking into account various parameters such as indoor air temperature, VAV mechanical ventilation control, and CO_2 level to minimize the cooling need in an open-plan office building, located in the center of Glasgow, Scotland. The results showed that the hybrid ventilation system in the best case can save up to 75% of air handling unit (AHU) fan energy. However, the space heating increased about 60% in this case. Liu et al. [6] examined window and thermostat use data collected from two mixed-mode ventilation buildings in Ottawa, Canada. The objective was to create operational sequences for variable air volume (VAV) terminals and offer occupants guidelines for opening windows during favorable indoor and outdoor conditions. Nevertheless, the study did not investigate the environmental factors that indicate whether natural ventilation results in energy savings or the energy-saving potential associated with it.

Peng et al. [7] conducted a comprehensive review on the control strategies of hybrid ventilation in mixed-mode buildings in diverse climates. Their analysis of the control parameters used in hybrid ventilation revealed that indoor air temperature was the most commonly utilized parameter, followed by relative humidity and CO_2. With regard to outdoor conditions, outdoor temperature was the most frequently chosen parameter, followed by wind speed and relative humidity. In terms of building-related information, the results showed that window status (on/off) was utilized in the majority of studies, followed by supply air temperature and temperature setpoints.

Although there is a growing interest in hybrid ventilation system control, there is still a lack of comprehensive research on this topic in cold climates. This is primarily due to the complexity of the system and the challenges posed by indoor-outdoor airflow interactions, which can be disruptive in such climates. In this article, an automatic window opening method is proposed to achieve optimal control of hybrid ventilation systems in different building types located in cold climates. The primary goal of this method is to use window opening as a natural ventilation method to downsize the air handling unit (AHU) while meeting the cooling needs of the building and maintaining indoor air quality and thermal comfort for occupants. Ultimately, this may lead to a reduction in total building energy use.

3. Modeling and simulation method

The present investigation involved the utilization of the IDA Indoor Climate and Energy (IDA ICE) tool as a dynamic building energy simulation software, with the aim of simulating and assessing the effectiveness of the hybrid ventilation control method. The subsequent sections outline the modeling and simulation procedures implemented through the IDA-ICE tool.

3.1. Case study and building energy model details

As a case study, a building model representing a mixed-mode office landscape located on the middle floor of a typical office in Norway (as shown in Figure 1) was analyzed. The building envelope properties, lighting system, HVAC system, and setpoints were all selected in accordance with the specifications of the Norwegian building code TEK17 [8].

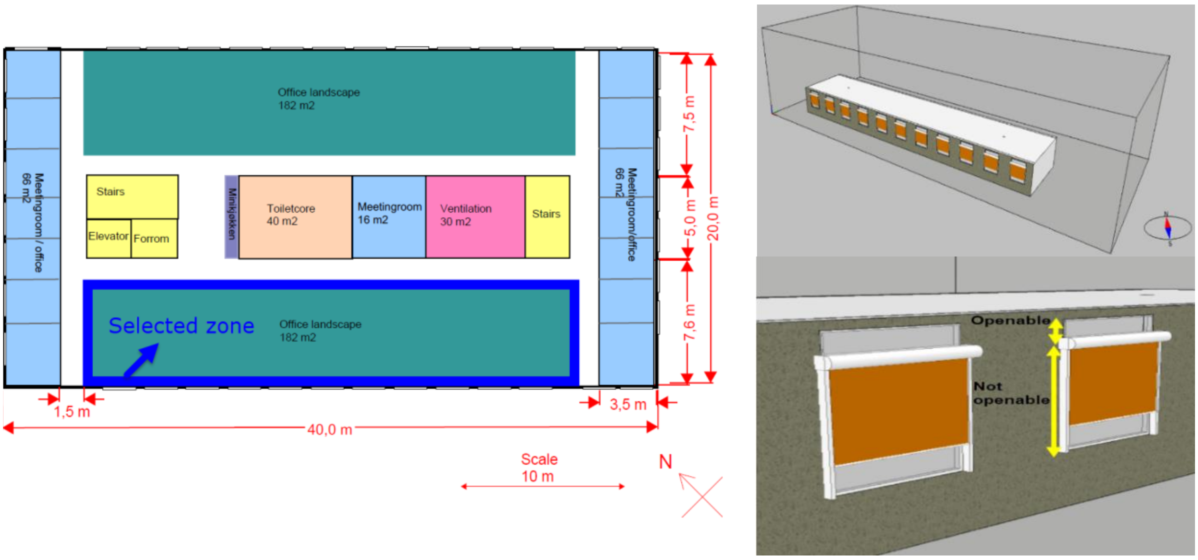

Figure 1**.** Selected office landscape for the simulations (left), and 3D model of the office landscape in IDA-ICE with two-parts window (right)

The room is equipped with water radiators placed on the external walls (under windows). The windows have been divided into two distinct sections. The lower part, which is 1.8 meters in height, is larger and equipped with an automated external solar shading system. This part of the window is not openable. The upper part, which is 0.4 meters in height, is smaller and can be opened, as demonstrated in the image on the right-hand side of Figure 1. presents the building envelope properties of the office landscape and internal gains due to occupancy, equipment, and lighting along with their usage profiles chosen in accordance with the Norwegian standard specifications SN-NSPEK 3031 [9]. In simulations, the weather data for Blindern station in Oslo, obtained based on Standard NS-EN ISO 15927-4, is used [10] .

Table 1. Details of the building envelope properties and internal gains for the office landscape

Parameter, Units	Value/properties
Floor area, m^2	180
External wall U-value, $W/(m^2.K)$	0.18
Glass U-values, $W/(m^2.K)$	0.70
Glass solar heat gain coefficient g-value	0.50 (0.05 with solar shading)
Normalized thermal bridge ψ, $W/(m^2.K)$	0.06
Infiltration n_{50}, 1/h	0.60
External solar shading strategy	Blinds on, if Q_{sol} > 175 W/m^2, outside window
Internal gains (persons/lighting/equipment)	6 m^2 / 8 W/m^2 /25W/m^2
Usage profile of internal gains	Based on NSPEK 3031 for office buildings [9].

3.2. Ventilation control strategies

This article compares two ventilation scenarios for the office landscape. The first case employs full Variable Air Volume (VAV) mechanical ventilation, with CO_2 and temperature controllers set to a constant supply air temperature of 18°C throughout the year. The average efficiency of heat recovery system and the average specific fan power (SFP) in the mechanical ventilation system are 0.8 and 1.5 $kW/(m^3.s)$, respectively. The minimum and maximum airflow rates for this case are set to 2.5 $m^3/(h.m^2)$ and 16 $m^3/(h.m^2)$, respectively, with corresponding minimum and maximum air temperature and CO_2 setpoints of 21-23°C and 400-900 ppm, respectively. Through simulations, the optimal airflow rate is determined to meet the thermal comfort and indoor climate standards outlined by the Norwegian Labor Inspection Authority [11]. The mechanical ventilation system also takes advantage of night ventilation during non-occupied hours. The second case utilizes a hybrid ventilation system that combines VAV mechanical ventilation controlled by air temperature and CO_2 with natural ventilation via automatic window opening control. The mechanical ventilation airflow rate in the hybrid system is considered to be 12 $m^3/(h.m^2)$.

Figure 2 illustrates a hybrid ventilation system that utilizes natural ventilation. This system is modelled in IDA-ICE and includes control areas that determine how window openings are automatically controlled.

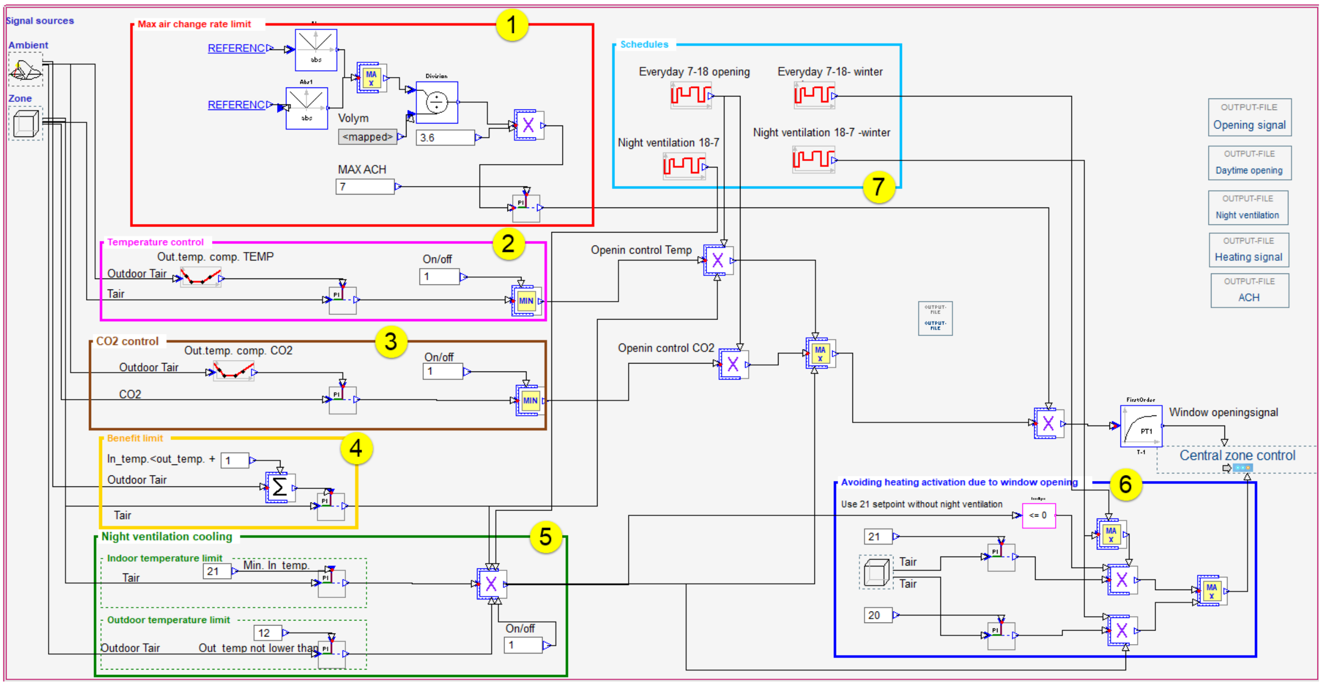

Figure 2. Schematic of the developed window opening control in the hybrid ventilation system.

The hybrid ventilation control system operates by prioritizing the mechanical ventilation system, which takes precedence over the window opening. However, if the air temperature and CO_2 levels in the designated control areas (2, 3, and 5) exceed their setpoints, the window opening mechanism will activate. Specifically, if the indoor air temperature surpasses 24°C and is higher than the outdoor temperature by at least 1°C (control area 4), or if the CO_2 level exceeds 950 ppm, the windows will open automatically between 7:00 am and 6:00 pm (control area 7). During non-occupancy hours (between 6:00 pm and 7:00 am), the windows will open if the indoor air temperature is higher than 21°C, the outdoor temperature is higher than 12°C, and the indoor air temperature is higher than the outdoor temperature by at least 1°C. Throughout the day, the maximum air change per hour (ACH) through the windows is an additional constraint that limits the automatic window opening (control area 1). The degree of opening is automatically adjusted to meet the specified requirements. In addition, the heating system operates if the indoor air temperature falls below 21°C throughout the day. However, if the night ventilation is activated the heating setpoint is reduced by 1°C (heating setpoint 20°C) to avoid simultaneous operation of window opening and radiators (control area 6).

4. Results

In this section the results obtained from indoor thermal climate and energy simulations of the office landscape are presented for the full mechanical ventilation and hybrid ventilation cases.

Figure 3 indicates the variation in indoor and outdoor air temperatures within the office landscape, as well as the verification of the window opening control method, during both an Oslo dimensioning summer day and a day in the spring (specifically, May 12th). During occupied periods, the window opening is regulated by the dominant temperature, rather than CO_2 levels. On the spring day, the night ventilation mode is enabled after occupied hours between 18 and 20:30, when the outdoor air temperature exceeds 12°C and indoor air temperature is above 21°C. The heating signal is then activated shortly to maintain the air temperature above the 20°C set point. However, on the summer day, the night ventilation mode is continually activated outside of occupied hours as the outdoor temperature remains above 12°C, validating the effectiveness of the automatic window opening control method.

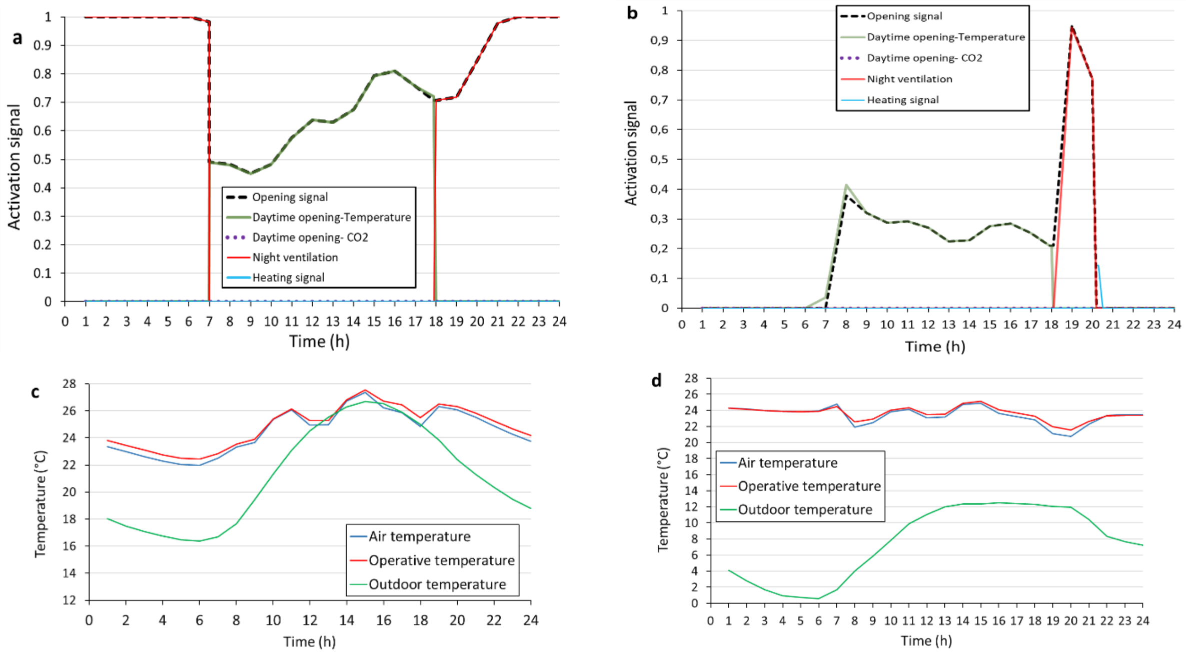

Figure 3**. a** and **b** verification of activation signal, and **c** and **d** variation of indoor and outdoor air temperature during an Oslo dimensioning summer day (**a** and **c)** and a day in spring (May 12th) **(b** and **d).**

Figure 4 presents a comparison of the annual energy consumption of fans, ventilation cooling, and space and ventilation heating in the office landscape, between mechanical and hybrid ventilation systems. Despite the implementation of night ventilation in the mechanical ventilation system, the cooling demand in the hybrid ventilation system is approximately 25% lower than in the mechanical ventilation system. In addition, the use of fans is reduced by approximately 26% due to window opening. However, the energy consumption for heating increases about 4%. Overall, the total energy consumption for fans, cooling, and heating is still approximately 24% lower in the hybrid ventilation system compared to the mechanical ventilation system.

Figure 5 indicates the variation of average operative temperature during the entire year. The operative temperature meets the adaptive temperature limits determined based on standard NS-EN-15251 [12].

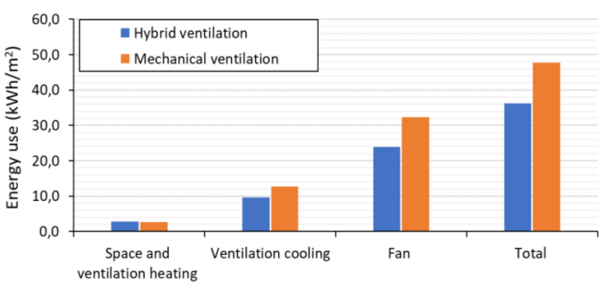

Figure 4. Comparison of investigated ventilation strategies in terms of energy use.

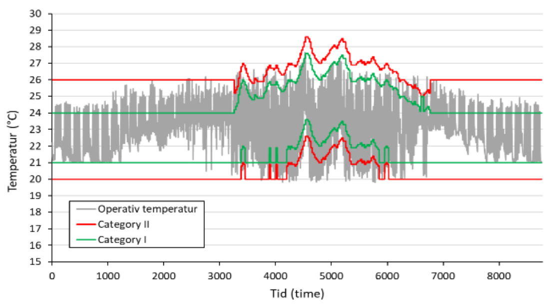

Figure 5. Variation of operative temperature for the hybrid ventilation throughout the entire year.

The Category II maximum temperature limit is surpassed for a total of 39 hours, a value that is within the maximum limit established by the Norwegian building code TEK17 (50 hours). The minimum temperature limit is not met, during unoccupied hours in the summer season, due to night cooling. But temperatures within Category II limits are met at the start of the working day. Furthermore, the hybrid ventilation system is found to be capable of maintaining a maximum CO_2 level of 850 ppm throughout the year.

5. Conclusions

The study aims to model and evaluate a hybrid ventilation system consisting of mechanical ventilation with automatic window opening as a means of natural ventilation for an office landscape in a cold climate. The objective is to investigate whether such a hybrid system could be used as a sustainable ventilation solution for different building types in similar climatic conditions. The automatic window opening was regulated by various parameters, including outdoor and indoor air temperature, CO_2 level, and ACH, which can be modified for different building types. The performance of the hybrid ventilation system was assessed by comparing it with a mechanical ventilation system. Results indicates that although the hybrid system increases the building's heating needs slightly, it reduces the cooling and fan energy consumption to a greater extent, resulting in a 24% decrease in the total energy use for cooling, heating, and fan compared to the mechanical ventilation system. The hybrid system also meets the indoor thermal climate, indoor air quality, and thermal comfort requirements of occupants.

It should be noted that the proposed control method will, in our further work, form the basis for life cycle analysis of ventilation system emissions and the development of "green ventilation" solutions for diverse building types in cold climate countries such as Norway.

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