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# Simulations of a novel demand-controlled room-based ventilation system for renovated apartments

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# Simulations of a novel demand-controlled room-based ventilation system for renovated apartments

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**Abstract.** The study simulated and assessed a novel control algorithm for an innovative room-based ventilation system for renovated apartments. The novel system is a manifold of fans that connects to an air-handling unit to control the supply of airflow to each room in an apartment. The exhaust side has a 3-way damper to control the division of extract airflows. The simulation required demand-control of ventilation airflows in each room. This included $CO_2$- and temperature-based control of supply to dry rooms and humidity- and temperature-based control of exhaust from wet rooms. The object-oriented software IDA-ICE includes a graphical interface for assembling the controls, which enabled custom simulations. The controls efficiently maintained sufficient air quality in each room and ensured balance of supply and exhaust. The room-based demand-controlled ventilation system achieved 74% savings in fan energy consumption relative to the reference constant air-volume system. The simulations indicated the need for less-resisting overflow vents in doorways to prevent infiltration heat loss when supplying bedrooms with greater airflow. Infiltration heat losses increased by 18% with closed doors despite the use of acoustic vents to assist overflow. Future measurements will aim to validate the demand-control algorithm and the performance of the novel system in real apartments.

## 1. Introduction

Many governments have targeted energy savings to reduce greenhouse gas emissions and limit anthropogenic climate change. In Denmark, heating in buildings is responsible for 26% of final energy consumption [1], and renovations could provide significant savings [2]. A Danish national action plan therefore expects to reduce heating consumption in the current building stock by at least 35% before 2050 [3]. Many existing apartments rely on mechanical exhaust to draw fresh air through cracks and orifices in the building envelope. Renovations improve airtightness [4] and require new supply points to maintain adequate air quality [5]. Some renovations provide fresh air through acoustic vents in the façade, but this limits options for heat recovery. Air-to-air heat exchangers require a point of intersection between supply and exhaust. Decentralised ventilation applies heat recovery in every zone or apartment, which reduces the need for ductwork. This limits energy consumption due to frictional losses and limits the spread of smoke in case of fire. It also enables renovation of single apartments, and it reduces the necessary time for planning and installation. This has motivated the development and application of air handling units (AHUs) that serve single apartments. These AHUs use all the conventional components of multi-dwelling AHUs, such as supply and exhaust fans, air filters and a heat exchanger, but in a smaller form. An apartment-level AHU is relatively small and can fit into a lowered ceiling with small ducts connected to all rooms. Many systems include sensors for feedback-control of the indoor climate via actuation of the fans and modulation of heat recovery. Morelli et al. [2] installed a whole-dwelling constant air-volume (CAV) ventilation unit in a renovated Danish apartment and stated the need for demand-controlled ventilation due to high incidences of open windows, which resulted in excess mechanical ventilation.

These AHUs typically ventilate an entire apartment as a single zone. However, occupants will often perform different activities in each room, and renovated buildings are especially sensitive to gains due to greater retention of heat and air. In Denmark, many occupants sleep with their window open at night. If the AHU extracts air from a naturally ventilated room, it substantially reduces the effective heat recovery of the system. Such a system should respond by minimising mechanical ventilation where appropriate. Similarly, the system should increase airflows to occupied rooms to achieve the desired level of indoor air quality. This requires control over the supply airflow to each room, and this paper describes a novel technology and system for this purpose. It further describes simulations to predict its performance in a real demonstration case.

Many building simulation programs lack modularity, which hinders their ability to simulate innovative systems [6]. The platform IDA-ICE provides the necessary user-interface and modularity of components to model and simulate apartment-level AHUs with room-based demand-control. The authors simulated such a system to assess its impact on a renovated apartment in Denmark. The paper describes and reviews the performance of the system with respect to energy and indoor air quality.

## 2. System description

The ventilation system comprised of an apartment-level AHU, a distribution manifold, a three-way valve to control exhaust airflows, acoustic-dampening overflow vents in each doorway, a sensor module in each room and a control system. The system currently operates with constant air-volume flowrates in eight renovated apartments in Denmark. In the autumn of 2019, four apartments will start using the room-based demand-control devised and simulated in this work.

### *2.1. Air-handling unit*

The reference ventilation system uses an AHU from Airmaster (model CV200). This AHU is suitable for single apartments as it provides greater than 80% dry heat recovery and has a ventilation capacity of roughly 90 L/s at 100 Pa of external resistance. The commissioning process requires installers to specify maximum fan signals for supply and exhaust to achieve balanced airflows. If the system has variable air-volume (VAV), modulation applies to both supply and exhaust to maintain balance. This also applies to boosted kitchen exhaust. The AHU can receive external control signals for airflow and supply temperature. The latter signal modulates a bypass damper to divert a fraction of the supply air around the heat exchanger.

### *2.2. Distribution manifold*

A typical system may employ dampers to control individual airflows instead of fans, but this introduces complications with balancing supply and exhaust. Frictional losses have a non-linear relationship with airflow, so each distribution yields a different resistance, which could lead to an unbalanced system. Furthermore, dampers throttle airflows and reduce overall energy efficiency [7].

To enable efficient room-based demand-controlled ventilation, the company ebm-papst developed a manifold of fans with duct connections for each supply line. Figure 1 shows a sketch of the manifold, which uses compact DC axial fans. The manifold includes pressure differential sensors to measure the pressure rise from each fan at a given control signal and fan speed. This provides a known duty point for calculating the expected airflow. The control system calculates and sums these airflows and requests the same airflow from the AHU. The AHU and manifold provide pressure the rise upstream and downstream of the manifold, respectively, and the commissioning process reflects this.

During commissioning of the AHU, the chamber of the manifold is open, so the supply air travels directly into the corridor and bypasses the supply duct, diffuser and overflow vents. With such a configuration, the AHU overcomes pressure losses upstream of the manifold. During operation, the fans in the manifold overcome downstream pressure losses, including the supply duct, diffuser and overflow vents between rooms. This ensures that the AHU does not supply excess pressure to the manifold since this would result in excess airflow to rooms with no demand. Without elevated pressure ahead of the fans, the fan signal provides accurate control of airflows.

### *2.3. Exhaust distribution*

In theory, the system could use the same type of manifold to control exhaust airflows. The only difference would be the orientation of the fans, which would instead pull air from the rooms. The commissioning process would be similar, with the manifold open to the corridor. Such a system would allow independent control of airflows from the kitchen, bathroom and other wet rooms in a balanced system.

In reality, the system uses a three-way valve to control the division of airflows on the exhaust side. The valve position affects the balance of supply and exhaust due to changing resistances. If the system extracts all air from the kitchen hood, the resistance increases and the total airflow decreases. This is due to the non-linear relationship between airflow and resistance. Furthermore, the kitchen hood could use a grease filter, which exacerbates the issue. With insufficient exhaust, the system has excess supply air, which results in exfiltration and excess heat loss. Therefore, the controller of this system must constrain the division of airflows to maintain constant indoor pressures and ensure overall balance.

### *2.4. Overflow vents*

An important consideration for such a system is the overflow vent in each room. Many modern interior doors use narrow seals or gaps to restrict noise transmission, but this restricts airflow as well. When employing demand-controlled ventilation with relatively high aims for air quality, the airflow rate between rooms can far exceed typical values. The system intends to supply up to 10 L/s per person, as recommended to achieve the highest category of air quality according to standard ISO Standard 15251 [8], so closed doors must not restrict airflow excessively. Table 1 shows the relationship between pressure difference and airflow for the acoustic vent installed in the renovation.

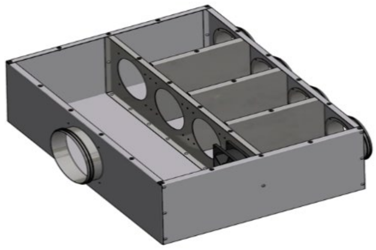

**Figure 1.** Drawing of the distribution manifold.

**Table 1.** Manufacturer data for an acoustic door vent.

| *Pressure across door [Pa]* | *Airflow per unit length [(L/s)/m]* |
|---|---|
| 1 | 5 |
| 2 | 7 |
| 10 | 15 |
| 20 | 22 |

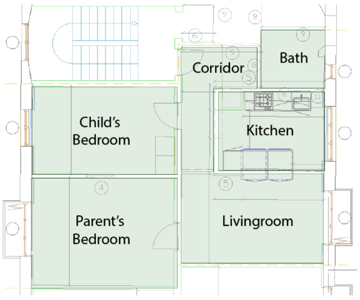

**Figure 2.** Floorplan of the demonstration site.

### *2.5. Control algorithm*

To enable room-based demand-control, the system applies sensor modules in each room. The modules measure several properties of the indoor air, including temperature, relative humidity, carbon dioxide concentrations and sound levels. The modules transmit average measurement data in 5-minute intervals to a central controller in the Cloud. The controls target carbon dioxide, relative humidity and temperature. ISO Standard 15251 [8] provides performance categories for each. The upper limit on carbon dioxide is 350 ppm above ambient concentrations for category I air quality. The upper limits on relative humidity in categories I and III are 50% and 70%, respectively. To assess thermal comfort, the standard uses operative temperature and limits it to 25.5 °C and 27.0 °C for categories I and III, respectively. Category IV is defined as only being acceptable for a "limited part of the year".

The algorithm employs a proportional controller to vary airflow rates in each room. The controller proportionally increases airflows for measured values between the lower and upper bounds. These bounds are 750 ppm and 850 ppm for carbon dioxide. The bounds for temperature are 25 °C and 27 °C, respectively, which should be high enough to avoid concurrent heating (e.g. radiators) and free cooling (e.g. venting). The bounds for humidity ratio are 0.008 $\mathrm{kg_{H2O}/kg_{AIR}}$ and 0.012 $\mathrm{kg_{H2O}/kg_{AIR}}$. At an assumed room temperature of 21 °C, these humidity ratios correspond to roughly 52% and 77% relative humidity. Since the indoor temperatures remain within a limited range for comfort, the authors regard the use of humidity ratio as sufficient.

The proportional controller is all that is necessary to limit carbon dioxide concentrations. Ambient concentrations remain stable at approximately 400 ppm, so ventilation always contributes to reducing CO2 concentrations. This is not true for relative humidity or temperature as the ambient conditions vary over time. Therefore, the algorithm ensures sufficient drying or cooling capacity before applying their respective gains. To ensure drying capacity, the algorithm compares indoor and outdoor humidity ratios. Drying is only be active if the outdoor air contains at least 0.003 $kg_{H2O}/kg_{AIR}$ less humidity than indoor air. To avoid rapid oscillations, the algorithm employs another proportional band to smoothen the transition. The algorithm only applies humidity-based control in the kitchen and bathroom since the moisture sources in other rooms are less prone to extremes [9]. The algorithm employs a similar method to ensure cooling capacity when limiting indoor temperatures. The algorithm only applies the airflow gain if the outdoor air is at least 4 °C cooler than the indoor air. To avoid oscillations from changes to cooling capacity, the controller employs 2 °C of smoothing.

In all living rooms and bedrooms (i.e. dry rooms), the algorithm only set limits on temperature and carbon dioxide because the humidity derives from CO2-emmiting occupants. In the bathroom, the algorithm only limits humidity and carbon dioxide because occupants often prefer warmer bathroom temperatures. In the kitchen, the algorithm limits all three variable since they may have independent sources. In each room, the algorithm takes the maximum control signal. The algorithm sums all supply airflows and all exhaust airflows. It scales the lesser sum to be equal to the greater sum while maintaining similar proportions between rooms. This ensures balance of supply and exhaust. The manifold allows connections to four rooms, but the renovated apartments use only three rooms.

The algorithm also controls the supply temperature from the main AHU by modulating heat recovery within a comfortable range. It attempts to track a setpoint for return air temperature in order to limit overheating. It is more energy efficient to bypass heat recovery than to boost ventilation rates to limit overheating due to the difference in fan power. For this reason, the return temperature setpoint for the AHU is 25 °C in this implementation.

In total, eight apartments received the manifold for testing at a demonstration site. Four of these apartments served as reference sites with empty manifolds, while the other four apartments received fully functional manifolds. There were two types of floorplans, and this paper focuses on one of these. Figure 2 shows the floorplan used in simulations.

## 3. Simulation methods

IDA-ICE is an effective tool for simulating custom control algorithms in buildings. The following describes several relevant aspects of the apartment model.

### *3.1. Internals loads*

The simulations used similar occupancy and load profiles to earlier room-based investigations [9]. Each adult released $CO_2$, moisture, and heat according to equations from standard EN ISO 7730 [10]. Each child represented the equivalent of 0.6 adults. The moisture gain from cooking corresponded to 0.2 kg per 30 minutes. Breakfast and lunch released 0.2 kg and dinner released 0.6 kg. Similarly, Hite and Bray [11] listed moisture gains from breakfast, lunch, and dinner as 0.17 kg, 0.25kg, and 0.58 kg, respectively, if cooked with an electric element. The total daily moisture gain from showering was 1.6 kg based on measured data by Yik *et al.* [12]. Their study calculated the moisture release from a single -shower to be 0.53 kg. Simulations neglected all other moisture sources.

The simulations used a proportional-integral controller to mimic occupant behaviour for opening windows. The controller attempted to track 25 °C inside the room during the period from April 15th to September 15th on the condition that outdoor temperature was lower than indoor temperature. This provided a supplement of fresh air that reduced the demand for mechanical ventilation in summer.

### *3.2. Modelling of leakages*

According to Shah and Sekulic [13], you can estimate the mass flow through an orifice using Equation 1, where Cd is the dimensionless coefficient of discharge, $A_o$ is the orifice flow area, $\rho$ is the air density and $\Delta p$ is the pressure difference across the orifice. IDA-ICE uses this equation to model pressure-driven leakage between zones. The authors used a Cd of 0.72, which is suitable for slot flow through an acoustic vent. Equation 2 shows the calculation of leakage area using the data from Table 1. The result is 0.005 $m^2$ for all combinations. The default leakage area for doors in IDA-ICE is 0.010 $m^2$, which is double the calculated leakage area of the acoustic vent. With insufficient leakage area, rooms may experience over- or under-pressure, which drives excess exfiltration or infiltration respectively.

$$\dot{m}_{\mathrm{leak}} = C_d A_o \sqrt{2\rho\Delta p} \tag{1}$$

$$A_o = \frac{\dot{m}_{\mathrm{leak}}}{C_d\sqrt{2\rho\Delta p}} = \frac{1.2\,\frac{\mathrm{kg}}{\mathrm{m}^3} \times 0.015\ \mathrm{m}^3/\mathrm{s}}{0.72\sqrt{2 \times 1.2\ \mathrm{kg/m}^3 \times 10\ \mathrm{Pa}}} = 0.005\ \mathrm{m}^2 \tag{2}$$

The simulations also required pressure-driven leakage rates in the façade. Using the average measurements from the air quality sensors in all rooms, the authors analysed the decay of CO2 concentrations during an unoccupied period while the AHU was off for three consecutive days. Based on the exponential decay, the minimum air change rate was roughly 0.16 $h^{-1}$ or 0.11 L/(s $m^2$) on a windless day. The simulations included wind-driven infiltration by specifying an air tightness at 50 Pa. The authors used a rule-of-thumb to estimate the air tightness as 2 L/(s $m^2$ floor area) at 50 Pa.

### *3.3. Calculation of fan energy*

During commissioning, the installer measured 35 L/s on the supply and exhaust. The authors installed current meters to monitor the power demand of the eight AHUs based on an assumed voltage. The specific fan power (SFP) ranged from 900 J/$m^3$ to 1100 J/$m^3$. IDA-ICE allows input of SFP, so simulations used 1000 J/$m^3$. In the case of part-load, IDA-ICE adjusts the SFP according to Appendix G of ASHRAE Standard 90.1 [14]. The total consumption must include energy for the individual fans in the manifold. MagiCAD software estimated the pressure loss through the supply ducts, diffusers and acoustic vents based on manufacturer data at the nominal airflow, $V_{\mathrm{nominal}}$, which yielded nominal duty points for each fan. The fan curve provided the power demand at each duty point. For demand-controlled airflows, Equation 3 used the following affinity law for fan power at each actual airflow, $V_{\mathrm{actual}}$.

$$\mathrm{Power}_{\mathrm{actual}}\ [\mathrm{W}] = \left(\frac{\dot{V}_{\mathrm{actual}}}{\dot{V}_{\mathrm{nominal}}}\right)^3 \times \mathrm{Power}_{\mathrm{nominal}} \tag{3}$$

## 4. Results, discussion, and conclusion

The room-based demand-control algorithm effectively maintained the desired indoor air quality in regards to carbon dioxide concentration, relatively humidity and temperature in the simulated apartment. Figure 2 and Figure 3 show the duration curves of carbon dioxide concentrations and AHU airflows, respectively, in a full year. The carbon dioxide only exceeded the limit in the bathroom, which did not have CO2-based control. Furthermore, the relative humidity in the kitchen and bathroom only exceeded 60% (i.e. category II) for 26 hours and 950 hours, respectively.

**Figure 3.** Duration curve of $CO_2$ concentrations with room-based demand-control.

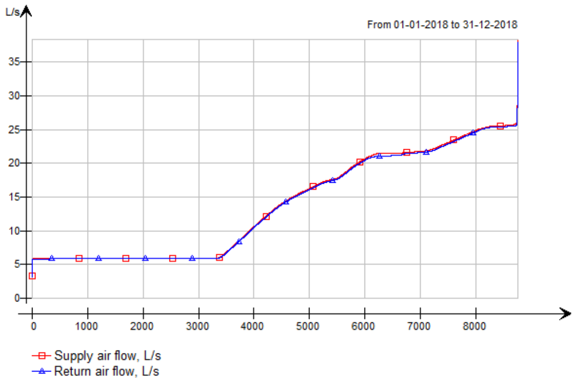

**Figure 4.** Duration curve of supply and exhaust airflows with room-based demand-control.

A consulting engineer specified 35 L/s for CAV operation of the AHUs in the reference apartments, which equates to 0.82 air changes per hour. Table 2 shows the simulated annual energy consumption of the AHU for three constant ventilation rates. Based on measurements, the pro-rated actual annual AHU power consumption ranges from 290 kWh to 350 kWh.

Comparatively, Table 3 shows the simulated energy consumption of the room-based demand-controlled ventilation system. The total annual consumption is 109 kWh, which represents an annual savings of 74% compared to the reference CAV system. The fans in the manifold account for less than 7% of the total energy consumption.

**Table 2.** Fan energy of reference CAV system.

| *Air change rate [h-1]* | *Ventilation rate [L/s]* | *Specific fan power [J/m3]* | *Fan energy [kWh]* |
|---|---|---|---|
| 0.5 | 21.3 | 430 | 80 |
| 0.82 | 35 | 1000 | 306 |
| 1 | 42.7 | 1400 | 520 |

**Table 3.** Room-based demand-controlled system.

| *Target of pressure rise from fan* | *Annual Energy [kWh]* | *Average airflow [L/s]* | *Maximum airflow [L/s]* |
|---|---|---|---|
| AHU | 103.8 | 13.8 | 25.6 |
| Child's bedroom | 0.2 | 2.9 | 7.2 |
| Adults' bedroom | 5.8 | 6.3 | 18.0 |
| Living room | 1.0 | 3.7 | 14.3 |
| Total | 109 | | |

The authors performed simulations of the demand-controlled system with all doors open or closed. This indicated the performance of the acoustic vents with regards to overflow. In the winter months from December to March, the simulations with closed doors yielded 18% greater infiltration heat losses. This implied that the acoustic vents limited overflow, which lead to greater over-pressure in bedrooms and under-pressure in the kitchen and bathroom. For such high ventilation rates to bedrooms, installations should use a less limiting acoustic vent to allow unrestricted overflow.

IDA-ICE includes default demand-based controllers for temperature, carbon dioxide or relative humidity, or options for some combination of these. However, these controllers scale the ventilation rates for both supply and exhaust in each zone. If a zone has only supply or exhaust, as is typical in residences, the controller scales only this airflow, which does not ensure balance. If the controller scales airflows according to the sensed variable in their respective zone, the total supply and total exhaust can vary significantly, which yields infiltration or exfiltration and its associated heat losses. Therefore, this paper implements a custom control algorithm to achieve balanced airflows.

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