Final report

1. Project details

Project title	System solutions for demand-control and continuous-commissioning of room-based ventilation in dwellings
File no.	64016-0042
Name of the funding scheme	EUDP
Project managing company / institution	Technical University of Denmark
CVR number (central business register)	30 06 09 46
Project partners	Danish Technological Institute; Aarhus University; Rönby.dk; Ekolab; Arup & Hvidt; Sustain Solutions; Neogrid Technologies; Ebm-papst; Smock Ventilation
Submission date	19 December 2021

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3. Summary

Energy renovations seek to improve the airtightness of dwellings, which then requires ventilation with heat recovery to maintain or improve energy-efficiency, indoor climate, and durability. The control of ventilation installed during renovations often considers a whole dwelling as one climate zone, which neglects differences between individual rooms. Renovations retain heat and air, so rooms become sensitive to gains from solar radiation, occupancy, moisture loads and pollutants. When controlled as a single zone, it is difficult to sense and react to loads. A common consequence is insufficient bedroom ventilation, which can affect occupant health and sleep quality.

The objective of the project was development and demonstration of residential ventilation controlled by demand in particular rooms. Furthermore, the project aimed to develop and demonstrate Cloud connected ventilation and thus enable monitoring of its performance as well as control via Internet. The goal was to synergize monitoring and control of indoor climate to enable “continuous commissioning” ensuring that the systems work as intended throughout their lifetime.

Two ventilation systems were developed and demonstrated. A fan-based air distribution box that enables precise control of airflow to individual rooms. The solution was supplemented with control algorithm, which considered both thermal environment and indoor air quality in particular rooms. The system was connected to a Cloud portal. Air distribution box was integrated into the decentralized ventilation system in four apartments in Copenhagen. Cloud based controller communicated with the air distribution box via a gsm gateway placed in the apartment. Moreover, data from indoor environmental quality loggers as well as operational data for air handling unit in the apartment were integrated into the cloud controller. Based on these data, the controller regulated particular fans in the air distribution box to keep set points regarding temperature, relative humidity as well as CO_2 concentration in particular rooms. As the project was delayed due to disagreement among consortium partners as well as the Covid-19 lockdown, it was not possible to realize the whole demonstration as planned. However, the results proved the functionality of the technological concepts as well as functionality of Cloud based control. Room ventilation units BREATHE 55 were connected to the Cloud for continuous performance monitoring. The solution was demonstrated in three apartments in Birkerød. The Cloud based connection enabled verification of unit’s functionality in several control modes, namely temperature and relative humidity control mode as well as frost protection control mode.

Performance of commercially available Metal Oxide Semiconductor (MOS) sensors measuring Volatile Organic Compounds (VOC) under different activities typical for residences (e.g. cleaning, cooking, painting, etc.) were studied in field-laboratory setting. The results showed that there were notable difference is performance of sensors from different producers. The results also showed that the sensors from well-established producers detected pollutants in comparable patterns. They seem to be applicable for the control of “boost” ventilation dealing with sudden increase of unwelcome pollution.

The project developed and demonstrated a method for online continuous commissioning. Data from air handling systems in particular apartments were analyzed with respect to temperature efficiency of the heat recovery, air flow balance across the units, heat recovery by-pass control, etc. The demonstration was extended from eight demonstration units to all 42 air handling units in the apartment building. The method was able to identify air handling units operating inefficiently because of faulty airflow settings, unbalanced airflows and even wrongly installed sensors.

The project conducted extensive simulation studies focused on testing the Cloud control algorithm as well as studying impact of different boundary conditions (e.g. wind pressure, apartment position) on the performance of room ventilation units. The data from simulations represent a technical basis for the financial model assessing benefits of room-based ventilation. It was however not possible to accomplish the development of the financial model itself.

Ebm-papst's air distribution box technology developed during the project has by now progressed to the stage of second prototype. Its first commercial version is planned for 2022.

Resume

Når ældre bygninger energirenoveres forbedres bygningens lufttæthed væsentlig, hvilket nødvendiggør installationen af ventilation med varmegenvinding for at forbedre energieffektiviteten, indeklimaet og bygningens levetid. Det ses dog at ventilation sjældent bliver installeret, og i de få tilfælde hvor den gør, kontrolleres den som én indeklima zone, der neglegerer behovet i individuelle rum. Renoveringer medfører at varme og luft i et større omfang bibeholdes, og rummene bliver mere sensitive overfor varmetilførsel fra solindfald, beboere, fugtproduktion og andre forureningskilder. Når ventilationen kontrolleres som én zone, er det svært at reagere på spidslaster. Konsekvensen heraf er ofte mangelfuld ventilation i soveværelser, hvilket har en effekt på beboernes helbred og søvnkvalitet.

Formålet med projektet var udvikling og demonstration af rum-baseret behovstyret boligventilation. Projektet havde endvidere til formål at udvikle og demonstrere Cloud-forbundet ventilation og dermed muliggøre præstations overvågning samt kontrol via internettet. Målet var at integrere monitorering og styring af indeklimaet for at muliggøre så kaldt "continuous commissioning". Dette sikrer, at ventilationssystemer fungerer efter hensigten i hele deres levetid.

To ventilationssystemer blev udviklet og demonstreret- en luftfordelingsboks integreret med decentral ventilation samt rum-baseret ventilations aggregat. Luftfordelingsboksen muliggør præcis styring af luftstrømmen til de enkelte rum. Løsningen blev suppleret med en kontrolalgoritme, som tager hensyn til både termisk miljø og indendørs luftkvalitet i de pågældende rum. Systemet er tilsluttet til en Cloud-portal. For demonstration blev luftfordelingsboksen integreret i decentral ventilationssystem i fire lejligheder i København. Cloud-baseret controller kommunikerer med luftfordelingsboksen via en gsm-gateway placeret i lejligheden. Desuden er data fra indeklimamålere samt driftsdata for ventilationsaggregatet integreret i Cloud-regulator. Baseret på disse data styrer regulatoren ventilatorer i luftfordelingsboksen for at overholde sætpunkter med hensyn til temperatur, relativ luftfugtighed samt CO_2-koncentration i bestemte rum. Da projektet blev forsinket på grund af uenighed blandt konsortiepartnere samt Covid-19 nedlukning, var det ikke muligt at foretage den planlagte demonstration i sin helhed. Resultaterne viste dog, at den ønskede funktionalitet var opnået både for de udviklede ventilationssystemer og Cloud-baseret regulering. Rumventilationsaggregater "BREATHE 55" blev tilsluttet til en Cloud-portal for kontinuerlig præstationsmonitorering. Løsningen blev demonstreret i tre lejligheder i Birkerød. Forbindelse til Cloud og tilhørende data visualisering muliggjorde verifikation af aggregatets funktionalitet i flere kontroltilstande, nemlig temperatur- og relativ fugtighedskontroltilstand samt frostbeskyttelseskontroltilstand.

Kommercielt tilgængelige Metal Oxide Semiconductor (MOS) sensorer, der måler flygtige organiske forbindelser (VOC) blev undersøgt. Målinger foregik i så kaldte feltlaboratorier hvor eksponering til forskellige aktiviteter, der er typiske for boliger (f.eks. rengøring, madlavning, maling, osv.) blev simuleret. Resultaterne viste, at der var bemærkelsesværdig forskel på ydeevnen af sensorer fra forskellige producenter. Resultaterne viste også, at sensorerne fra veletablerede producenter opdagede forurenende stoffer i sammenlignelige mønstre. Dette indikerer, at de kan med fordel bruges til styring af forceret ventilation, der håndterer pludselig stigning i uvelkommen forurening.

Projektet udviklede og demonstrerede en metode til "continuous commissioning". Data fra ventilationsaggregater i flere lejligheder blev analyseret med hensyn til varmegenvindingens temperatureffektivitet, luftstrømsbalance på tværs af aggregaterne, varmegenvindings by-pass styring osv. Demonstrationen blev udvidet fra otte demonstrationsaggregater til alle 42 aggregater i etageejendommen. Metoden var i stand til at identificere aggregater, der fungerede ineffektivt på grund af forkerte luftstrømsindstillinger, ubalancerede luftstrømme og endda forkert installerede sensorer.

Projektet gennemførte omfattende simuleringsstudier med fokus på at teste skystyringsalgoritmen samt at studere indvirkningen af forskellige randforhold (f.eks. vindtryk, lejlighedsposition) på ydeevnen af rumventilationsenheder. Data fra simuleringer repræsenterer et teknisk grundlag for den økonomiske model, der vurderer fordelene ved rumbaseret ventilation. Det var dog ikke muligt selv at gennemføre udviklingen af den økonomiske model.

Ebm-papsts luftfordelingsboks er nu nået frem til stadiet af en anden generationsprototype. Dens første kommercielle version er planlagt til 2022.

4. Project objectives

The objective of the project was to focus on the development, demonstration and continuous-commissioning of room-based demand-controlled ventilation. The aim was to connect the residential ventilation to the Cloud and thus enable monitoring of their performance as well as control via Internet. The project should synergize monitoring and control of indoor climate to enable new investment models as continuous commissioning should ensure that systems work as intended throughout their lifetime. Specific objectives for the particular parts of the project are summarized below:

Residential Ventilation Systems

- Sustain Solutions focused on further development of room-based ventilation units with heat recovery. The units should be internet enabled. The units should be controllable with variable speed fans and variable bypass of heat recovery.
- Ebm-papst aimed to develop a new fan-based air distribution box for efficient control of ventilation air into individual rooms. Each fan power correlates to a flow rate, which removes the need for costly flow sensors.

Smart control on a room level

- The project aimed to develop a supervisory control setup based on the internet connectivity of the ventilation systems as well as indoor environmental quality (IEQ) monitors installed in individual rooms. All measured data should be gathered in the Cloud.
- Connection of room-based ventilation units developed by Sustain Solutions to the Cloud should enable their continuous commissioning as their operational parameters can be analyzed and visualized for building operator.
- Cloud based controller should be implemented for the fan-based air distribution box. Based on measurements, the controller should determine appropriate ventilation rate for the individual room and send the control signal to the air distribution box. Air handling unit installed in the apartment should be controlled simultaneously.
- Moreover, data collected in the cloud should be further analyzed to enable continuous commissioning. This analysis does not directly influence ventilation in the apartment, but provides information about "health" of the system. It provides building operator key performance indicators for each ventilation unit/apartment. Building operator can than take adequate decisions (change filter, schedule repair, etc.)

Financial model

- Installations of room-based demand-controlled ventilation improve air quality and comfort while lowering or maintaining energy consumption, but this primarily benefits the occupant and not the investor. Convincing building owners to invest requires valid data, financial predictability and an improved incentive structure. Sustain Solutions develops a new legal and financial model to ensure these qualities.
- The model should be based on data collected in project's demonstration cases.
- Cloud based monitoring should provide both baseline values regarding intensity of ventilation, moisture load and occupancy prior to renovation as well as measure improvements after room-based ventilation was installed. In addition to energy savings and improved indoor climate, the model should take into account lower tenant turnover and fewer renovations due to moisture issues.

Utilization of Metal Oxide Semiconductor (MOS) sensors for detection of Volatile Organic Compounds

- Scientific part of the project focused on Metal Oxide Semiconductor (MOS) sensors for detection of Volatile Organic Compounds. The objective was to provide scientific judgement regarding their reliability for ventilation control and to compare performance of commercially available MOS VOC sensors to the performance of the state of the art CO_2 sensor with respect to ventilation control.

5. Project implementation

Project started in October 2016 and the original plan was the duration of three years. The project progressed according to the plan until November 2018 when a disagreement arose between IC-Meter and the other partners regarding the course of the project. IC-Meter practically stopped the work on the project, which led to a lack of deliverables and thus a delay in work on several work packages. In January 2019 the project partners agreed that IC-Meter would leave the consortium. The project group applied for an extension of the project until October 2021. The project group was searching for a new partner in the project until January 2020, when Neogrid joined the consortium. The project description was redefined and the work on the project restarted. The focus was mostly on demonstration of the developed systems. The work in 2020 and 2021 was negatively influenced by the Covid-19 pandemics. It hindered access to the laboratories for testing as well as the actual installation in test apartments. The full demonstration of the air distribution box was therefore launched in July 2021.

The aforementioned challenges resulted in the fact that the project implementation did not develop as foreseen. Due to the involvement of a new project partner, which was able to overtake the most critical tasks relatively quickly, the most of the project milestones were met. However, the several commercial milestones could not be fulfilled. Particularly a commercial Cloud based control solution, which was dependent on a co-operation between IC-Meter and other project partners and a financial model for benefits of room based ventilation, dependent on the results of measurement campaign in demonstration apartments.

The final deliverable of the project – a closing seminar introducing the developed technologies was postponed until the beginning of 2022. This allows to extend the data collection beyond the duration of the project and thus obtain more data, as the original demonstration period was not realized due to the above-mentioned delays.

6. Project results

6.1 Air distribution box for room-based ventilation by Ebm-papst

According to research by Gunner[1], replacing airflow dampers with fans enables airflow modulation to each room and can provide overall energy savings of roughly 16% in a residential installation. The potential of such a system extends well beyond the reduced pressure losses, fan energy and noise from avoiding throttling of airflows. If the system includes accurate airflow measurements from each fan, there is the potential to ensure

[1] Gunner, A. (2014). Indregulering med decentrale ventilatorer frem for spjæld sparer energi. HVAC magasinet: magasin for klima- & energiteknik, miljø, bygningsinstallationer & -netværk, 50(5), 14-18. http://www.techmedia.dk/HVAC-Magasinet.36.aspx

accurate commissioning of ventilation airflows and demand-controlled ventilation. The following explains the potential in more detail:

- Reduced noise: Dampers and adjustable diffusers provide added pressure loss to obtain the expected airflows. This pressure loss derives from funneling airflows through narrow gaps, increasing their turbulence and velocities. Noise correlates with pressure loss and air turbulence in fans and dampers. The datasheet for a typical residential diffuser – shown in Figure 1 for the Lindab AIRY – demonstrates this point. The noise and pressure loss decrease with increasing opening width, *a [mm]*, for a given airflow. Opening the diffuser completely and adjusting the airflows using the fans minimizes the noise and pressure loss from the diffuser. One may expect higher throw lengths, but residences often have sufficient mixing from convective flows. Therefore, a reduced throw length may even help to reduce draught. Lastly, throttling devices may be prone to rattling, so removing dampers may help limit noise.

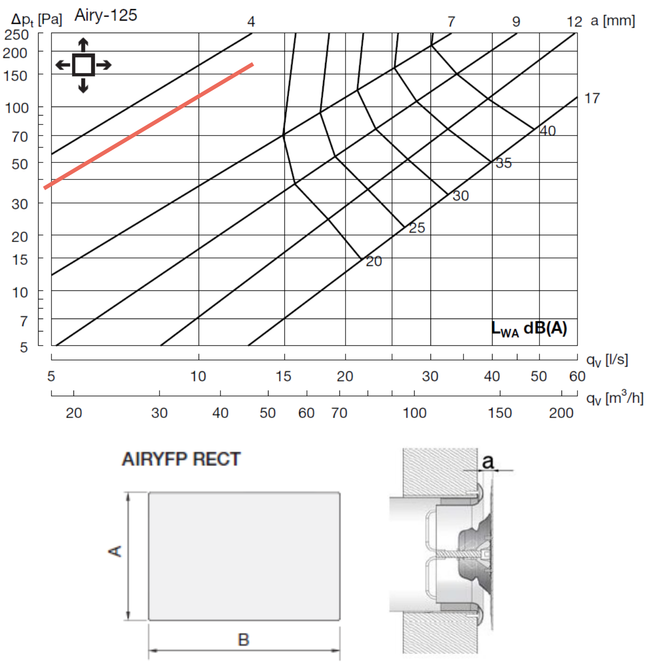


Figure 1. Lindab AIRY datasheet.


Figure 2. Adjustable diffuser valve.

- Fast, accurate and robust commissioning: Setting up a conventional system requires several commissioning iterations, on-site, by skilled technicians. The installer typically uses a balometer to measure airflows while performing this commissioning process. This process is often prone to error, either due to the relatively low accuracy of balometers at low airflow rates or due to difficulties positioning the balometers over top of supply or exhaust terminal devices. For example, the project purchased a re-commissioning of the ventilation system prior to configuring the novel Ebm-papst air distribution box due to suspicions of substantial airflow imbalances in the apartments. The author of the re-commissioning report needed to remove the front plates from the diffusers to fit the balometer. They observed that someone had completely screwed in the adjustable diffuser valves in many places, minimizing the gaps for airflow. They included a sample photo, as seen in Figure 2. Furthermore, Figure 1 shows that a fully closed damper (e.g. *a = 4 mm*) yields extremely high pressure losses or low flow rates. The closure of so many diffusers revealed a clear issue in the commissioning process that negatively affects indoor environmental quality (IEQ) and energy performance. Using individual fans to realize the correct airflows avoids such issues by removing the dampers or adjustable diffusers. Adding accurate measurements to each airflow would further enhance the commissioning process.

- Demand-based control: Commissioning with dampers represents a static system, whereas a system with an individual fan serving each room enables the use of demand-controlled ventilation. Whether manually or automatically controlled, the system can provide ventilation to rooms with a demand for fresh air while reducing ventilation to rooms without a need for it. As fan power has a cubic relationship to fan speed and airflow, any potential to reduce airflows without affecting IEQ can result in substantial energy savings. For instance, halving the airflow yields roughly one-eighth of the fan power.

Within the project, Ebm-papst developed the prototype of the air distribution box, which was consequently installed and operated in four test apartments at Ryesgade 25, Copenhagen.

6.1.1 Commissioning room supply airflows in air distribution box

Unlike the conventional ventilation system, where dampers ensure the proper air distribution, the general technical idea was to use fans to distribute the air from the main ventilation system. Such an approach leads to a decrease in pressure loss in the ventilation ducts, as dampers or adjustable diffusers would otherwise throttle flows and thus create high pressure losses, requiring greater fan energy. The prototype of the air distribution box was constructed with four supply ducts to serve a standard four-room apartment. Each duct was equipped with a variable speed fan, ensuring the particular room's flow. The air distribution box was placed next to the decentralized air-handling unit. Figure 3 depicts the installation of the air distribution box in one of the test apartments. Figure 4 shows the original prototype of the air distribution box. The solution opened the possibility of adding pressure differential sensors to commission the supply airflows.

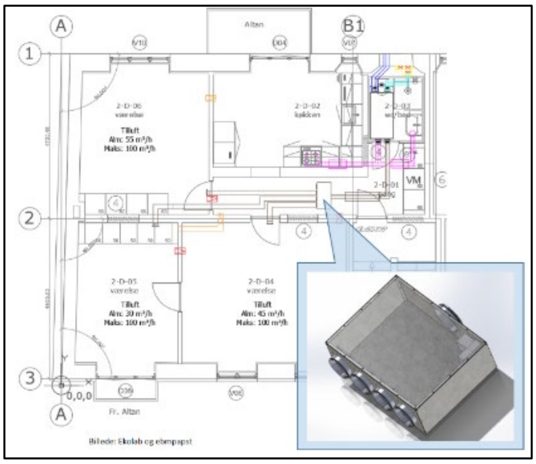


Figure 3. The floor plan of a demonstration apartment with the placement of air distribution box.

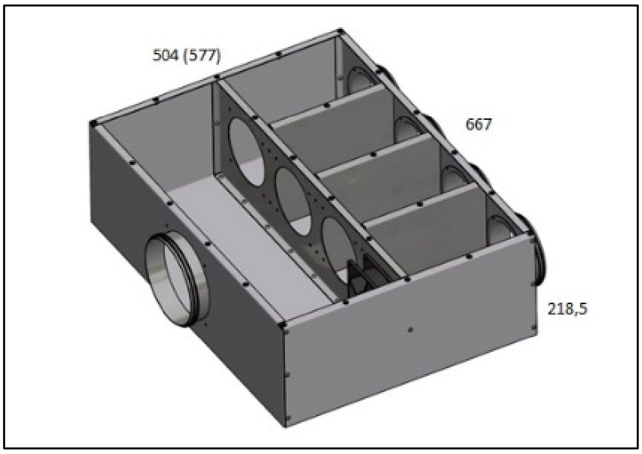


Figure 4. The early prototype of the air distribution box.

Before implementing the full solution in the apartments, the project tested the functionality of the air distribution box in the laboratory at Ebm-papst, as shown by Figure 5. During the early testing, the pressure was measured using manometers. The system curve was calculated, and finally, the needed output signal was manually created by turning knobs on the power supply.

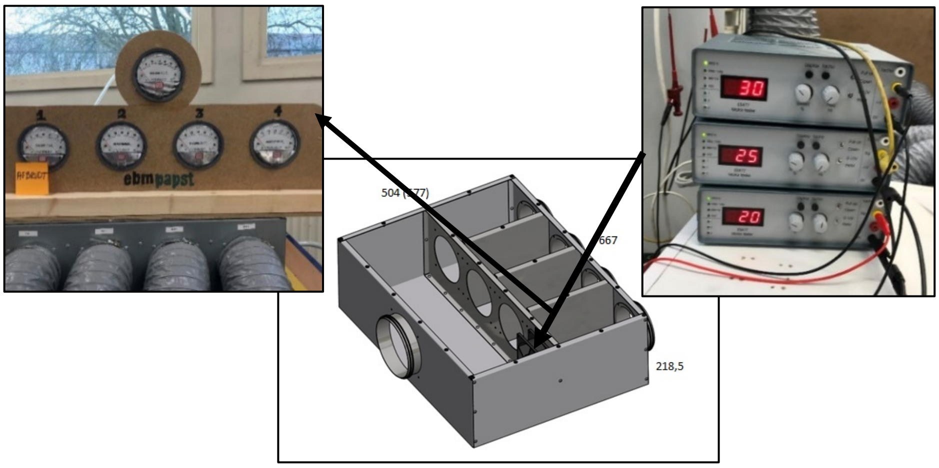


Figure 5. Early testing in the Ebm-papst's laboratory; pressure measured in the fan chamber and rotation speed adjusted on each fan.

Figure 6 illustrates the final testing of the overall design. Using an Airmaster CV200 air handling unit, exactly the same one as in the demonstration, the air distribution into several rooms was simulated using flexible ducting allowing to change pressure drop continuously. The requested flow to each "room" was obtained.

Figure 6. Final functionality testing of the distribution box.

Before starting the commissioning process in the actual demonstration apartments, the main chamber of the Ebm-papst air distribution box was opened to the corridor so that air could flow freely into the fans without any resistance. Pressure differential sensors measured the pressure rise across each fan, representing the pressure loss in the supply ducts and diffusers downstream. Initially, in the commissioning process, the fans were provided with various signals of up to 6 V (the maximum signal is 10 V) from the Cloud-based control system. However, a more systematic approach was needed to yield a reliable regression representing the relationship between the fan signals and pressures. Thus, the Cloud-based control system applied a routine with step intervals for the fan signals to obtain a clearly defined quadratic regression. Then the pressures at the maximum signal for each fan were determined by extrapolation. Ebm-papst has data representing the flow at the maximum fan speed for all possible pressure losses (i.e. a traditional fan curve) and converted this data to a mathematical expression. Thus, it was a simple task to calculate the airflow for the maximum signal with each fan and use the proportionality between fan signals and airflows to determine the necessary fan signal for any required airflow. A sensor also measured the pressure difference between the main chamber and the corridor to ensure that the main air-handling unit (AHU) provided the same airflow as the sum of the air distribution box's fans – i.e. the pressure differential sensor measured zero Pa between the corridor and the main chamber of the air distribution box.

Regarding the design of the air distribution box, it turned out that a model with two half-lids (one for the fan chambers and one for the main chamber to be opened during commissioning) would have made the initial calibration easier. Furthermore, the differential pressure sensor used were not able to measure negative differences, which should be avoided in the future (symmetric ranges are preferable when a 0 value is the aim). Regarding the calibration of the flows for each air distribution box fan, we had expected to be able to use the fan characteristic (airflow as a function of pressure) at full speed to identify air flows. However, the fan characteristic was sometimes non-monotonous, which made the reverse computation of flow based upon pressure difficult in a number of cases. We installed the system in several similar apartments with similar characteristics, which provided more data for defining the characteristic curves. Therefore, we were able to extrapolate values for all apartments.

6.1.2 Commissioning the main air handling unit (AHU)

All apartments in the building had a decentralized AHU from Airmaster A/S (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. This is achievable through a wired connection or a web API. The project used the API to control the Airmaster unit in the demonstration apartments.

During the Airmaster AHU commissioning, the chamber of the Ebm-papst's air distribution box was open to the corridor, so the supply air travelled directly into the corridor and bypassed the supply ducts to the rooms. With such a configuration, the main Airmaster AHU would only overcome pressure losses upstream of the air distribution box during operation – indicated in purple in Figure 7. During operation, the fans in the air distribution box would overcome downstream pressure losses (indicated in red in the same figure), including the supply duct, diffuser and overflow vents between rooms. This ensures that the AHU does not supply excess pressure to the air distribution box since this would result in excess airflow to rooms with no demand. Without elevated pressure ahead of the fans, they can accurately control room airflows. However, the control algorithm must ensure that the sum of the airflows from the air distribution box equals the airflow delivered by the main Airmaster AHU.

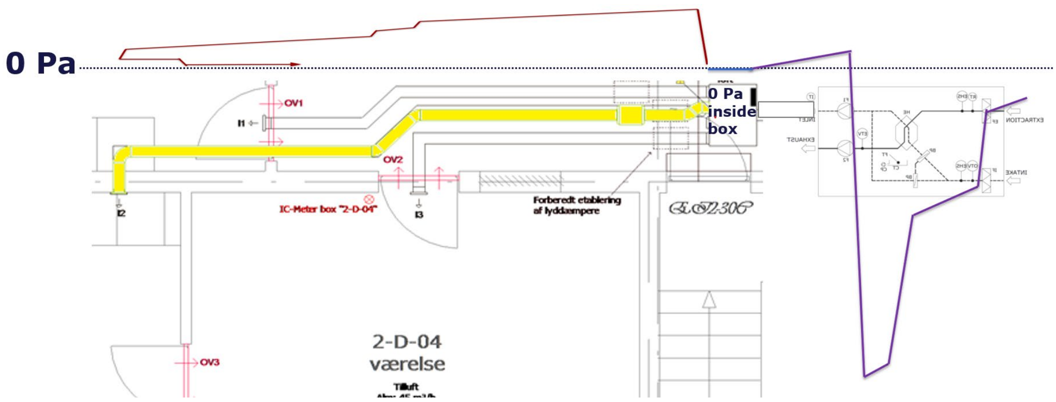


Figure 7. Rough schematic of the pressure loss in the system, where the main Airmaster AHU overcomes the pressure loss (**purple**) in the AHU and the ducts up stream of the air distribution box, whereas the Ebm-papst's air distribution box fans overcome the pressure losses (**red**) downstream of its fans.

Operation via a third-party API (Airmaster's Airlinq in this case) has proved to be challenging, both in terms of robustness of the API, which had apparently not been used on a large scale before and had some undiscovered bugs remaining which prevented operation in some occasions. Therefore, cabled operation between gateway and the air-handling components (e.g. with Modbus over RS485) would be preferable when this is possible (this was difficult here due to the layout of the apartments' technical systems).

6.1.3 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, restricting airflows. When employing demand-controlled ventilation with relatively high aims for air quality, the overflow from rooms can far exceed typical values. The system intends to supply 10 L/s per person, as recommended to achieve the highest air quality category according to standard DS/EN 16798, 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. The generally recommended maximum pressure loss across an internal door is 3 Pa. While the undercut gap below the door reduces the pressure loss through the acoustic vent by diverting some of the flow, the pressure loss might have been slightly high and affected performance. However, the selected vents – shown in Figure 8 - balanced cost, installation requirements and performance.

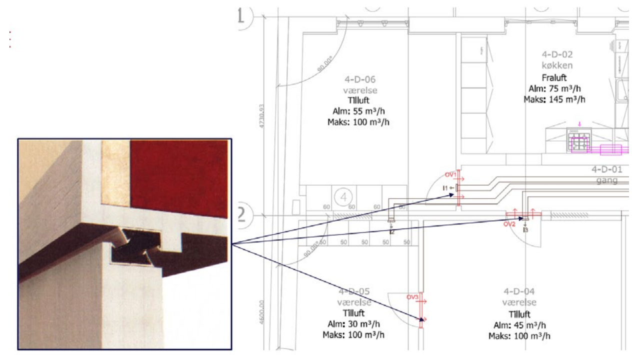


Figure 8. Installation of overflow vents.

Table 1. Manufacturer data for the acoustic door vent.

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

6.1.4 Considerations for exhaust airflows

Theoretically, the system could apply the same air distribution box to control exhaust airflows. The only difference would be the orientation of the fans, which would pull air from the rooms. The commissioning process would be similar, with the air distribution box 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 static three-way valve to control the division of airflows on the exhaust side.

6.1.5 The demand control algorithm

Based on the fan affinity laws and measured fan curves, we establish an algorithm yielding the required fan input voltage to provide the necessary airflows to meet demand. DTU and Neogrid implemented this and a final test was performed in September 2020.

To enable room-based demand-control, the system applies sensor modules in each room. The modules measure properties of the indoor air, including temperature, relative humidity, carbon dioxide and sound levels. The modules wirelessly transmit average measurement data in 5-minute intervals. The controls target carbon dioxide, relative humidity and temperature. DS/EN 16798 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 the relative humidity in categories I and III are 50% and 70%, respectively. The standard uses operative temperature to assess thermal comfort and limits it to 25.5 °C and 27.0 °C for categories I and III, respectively. Category IV is defined as only being accepted 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, as shown by Figure 9. The lower and upper bounds are 750 ppm and 850 ppm for CO_2. 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 kg_{H2O}/kg_{AIR} and 0.012 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 consider the use of the humidity ratio as sufficient.

A proportional controller can ensure sufficiently low carbon dioxide concentrations. Ambient concentrations remain stable at approximately 400 ppm, so increasing ventilation reduces CO_2 concentrations. This is not true for humidity or temperature as the ambient conditions vary over time. Therefore, the algorithm determines the drying or cooling capacity before applying these proportional gains. To ensure drying capacity, the algorithm compares indoor and outdoor humidity ratios. Drying is only active if the outdoor air contains at least 0.003 kg_{H2O}/kg_{AIR} less humidity than the indoor air. The algorithm employs another proportional band to smoothen the transition to avoid rapid oscillations. The algorithm only applies humidity-based control in the kitchen and bathroom since the moisture sources in other rooms are less prone to extremes[2]. 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.

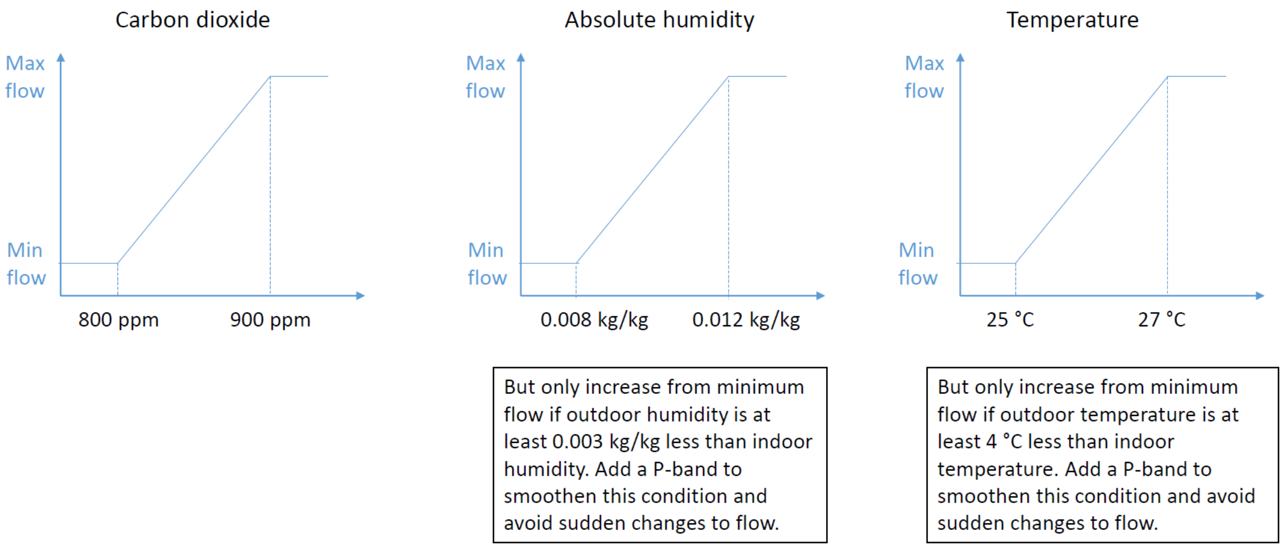


Figure 9. Schematic describing the proportional bands, capacity checks and smoothing in the proportional controller increasing the ventilation airflow to each room.

In all living rooms and bedrooms (i.e. dry rooms), the algorithm only limits temperature and carbon dioxide because the humidity mainly derives from CO_2-emitting occupants. The algorithm only limits humidity in the bathroom because occupancy is for short durations and occupants often prefer warmer bathroom temperatures. The algorithm limits all three variables in the kitchen 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

[2] Smith, K. M., & Svendsen, S. (2016). The effect of a rotary heat exchanger in room-based ventilation on indoor humidity in existing apartments in temperate climates. Energy and Buildings, 116, 349–361. https://doi.org/10.1016/j.enbuild.2015.12.025

airflows. It scales the lesser sum to be equal to the greater sum while maintaining similar proportions between rooms. This ensures a balance of supply and exhaust. The air distribution box can connect to four rooms, but the renovated apartments have only three supply 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 set point for return air temperature to limit overheating. It is more energy efficient to bypass heat recovery than boost ventilation rates to limit overheating due to increased fan power. For this reason, the extract air-temperature set point for the AHU is 25 °C.

Eight apartments received the air distribution box for testing at a demonstration site. Four of these apartments served as reference sites with empty air distribution boxes, while the other four apartments received fully functional ones. There were two types of floorplans, as shown by Figure 10.

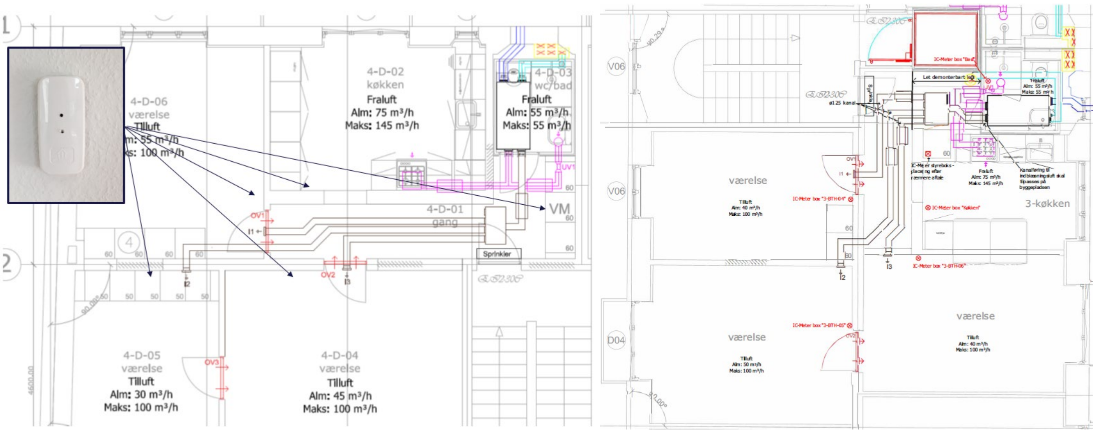


Figure 10. Floorplans for the two different apartment layouts, depicting the installed IC-Meter IEQ data loggers, air distribution boxes and ductwork to each supply room.

The control showed dynamical adjustment of both flow and supply temperature between zones, continuously adjusting supply to the different zones according to their indoor climate as well as the overall flow to the building.

The use of IoT (Internet of Things) sensors with a subscription was an extra cost in terms of subscription and mobile internet connection, which we could have avoided in the initial design by using sensors that could directly communicate to the gateway. The use of internet-based sensors has also required stronger fallback requirements in case of missing data from any of these. Nevertheless, the value of wireless IoT sensors is not questioned, as these are much more flexible, aesthetic and easier to maintain than their cabled counterparts are.

6.1.6 Simulation methods

Dynamic building performance simulation tool IDA-ICE (www.equa.se) was used for the simulations. IDA-ICE is an effective tool for simulating custom control algorithms in buildings, so we implemented the above-described algorithm to assess its performance. The algorithm ensured balanced supply and exhaust airflows at all times. We made the following assumptions when simulating a demonstration apartment.

Internals loads: The simulations assumed occupancy and loads schedules emitting CO_2, moisture, and heat according to equations from standard EN/ISO 7730. Breakfast and lunch emitted 0.2 kg while dinner released 0.6 kg. Hite and Bray[3] reported similar values for breakfast, lunch, and dinner of 0.17 kg, 0.25 kg, and 0.58 kg,

[3] S.C. Hite, J.L. Bray, (1948) Research in home humidity control, Engineering Experiment Station, Research Series No. 106

if cooking with an electric stovetop. The total daily moisture gain from showering were 1.6 kg, based on measured data by Yik et al.[4], who reported that a single shower released 0.53 kg. Simulations neglected all other moisture sources.

Window opening: A PI-controller mimicked idealized occupant behavior for opening windows. Each window opened to provide cooling if the room temperature rose above 25°C and the outdoor air could provide cooling. This provided a supplement of fresh air that reduced the demand for mechanical ventilation in summer.

Door leakages: IDA-ICE uses the orifice flow equation to model the mass flow through each closed door as a function of differential pressure. Based on the manufacturer data for the acoustic vents, we calculated a leakage area of 0.005 m^2, which is half of the default leakage area in IDA-ICE.

Airtightness: Using the measurements from the air quality sensors in all rooms, the authors analyzed the CO_2 decay during an unoccupied period while the AHU was off for three consecutive days. The minimum air change rate was roughly 0.16 h^{-1} or 0.11 L/(s m^2) on a windless day. The authors used a rule-of-thumb to estimate the air tightness as 2 L/(s m2 floor area) at 50 Pa and applied this value to the simulations.

Calculation of fan energy: The installer measured 35 L/s on the supply and exhaust during commissioning, and current measurement on the eight AHUs provided an estimate of their energy use. Thus, the specific fan power (SFP) ranged from 900 J/m^3 to 1100 J/m^3 (assumed 1000 J/m^3). In the case of part-load, IDA-ICE adjusts the SFP according to Appendix G of ASHRAE Standard 90.1. The total fan energy consumption for the system includes the AHU and the individual fans in the air distribution box. We calculated the latter using Equation 1 based on the nominal duty points for each fan (from MagiCAD) and the the cubic relationship between power and airflow according to the fan affinity laws.

$$Power\ [W] = \left(\frac{Airflow}{Airflow_{nominal}}\right)^3 \times Power_{nominal} = \left(\frac{Airflow}{120\ m^3/h}\right)^3 \times 18\,W \tag{1}$$

Local shading from buildings: The solar gains from the surrounding buildings impact the demands for heating and ventilative cooling. Therefore, we added shading objects representing the surrounding buildings in the simulations based on estimations from Google Maps, as shown by Figure 11, Figure 12 and Table 2.

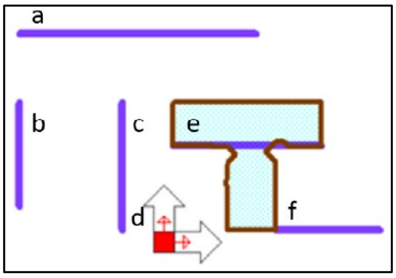


Figure 11. Surrounding 2D view.

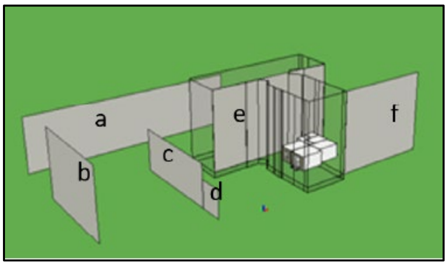


Figure 12. Surrounding buildings 3D view.

Table 2. Heights

Surrounding buildings	Height, m
a	11
b	13
c	8
d	5
e	16
f	16

6.1.7 Simulation results

The room-based demand-control algorithm effectively maintained the desired indoor environmental quality in the simulated apartment. Figure 13 and Figure 14 show the annual duration curves of CO_2 concentrations and AHU airflows, respectively. The relative humidity in the kitchen and bathroom only exceeded 60% (i.e. category II) for 26 hours and 950 hours, respectively.

[4] Yik, F. W. H., Sat, P. S. K., & Niu, J. L. (2004). Moisture Generation through Chinese Household Activities. Indoor and Built Environment, 13(2), 115–131. https://doi.org/10.1177/1420326X04040909

Figure 13. Duration curve of CO_2 concentrations with room-based demand-control.

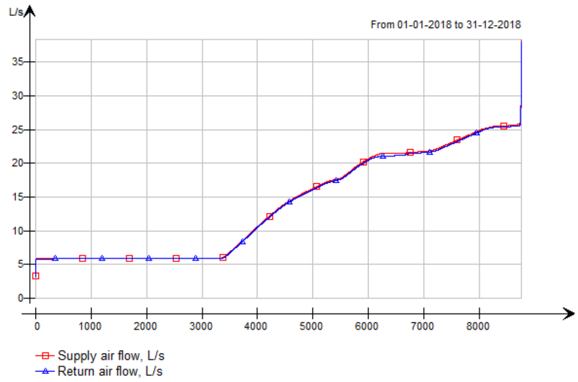


Figure 14. Duration curve of supply and exhaust air-flows with room-based demand-control.

A consulting engineer specified 35 L/s for CAV operation of the AHUs in the reference apartments, or roughly 0.82 ACH. Table 3 shows the expected annual energy consumption of the AHU at constant ventilation rates. According to measurements, the annual AHU power consumption likely ranges from 290 kWh to 350 kWh. Table 4 shows the simulated energy consumption of the fully room-based demand-controlled ventilation system. The simulated annual consumption was 109 kWh, representing an annual savings of 64% compared to the reference CAV system. The fans in the manifold accounted for less than 7% of the total.

Table 3. 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

Table 4. Room-based demand-controlled system

	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		

In simulations with closed doors, exfiltration heat losses increased by 18% in the four coldest months, indicating a need for acoustic vents offering less resistance to airflows.

In addition to the CAV and Room-based DCV systems, we extended the analysis to include a demand-controlled reference system (called 'VAV'), where the central AHU adjusts total airflow according to sensed humidity and temperature in the exhaust, and a demand-controlled system based on indoor climate sensors in each room but without the air distribution box. The latter case (called 'Room-based DCV without the manifold') had a fixed distribution of airflows that adjusted upwards if any of the rooms had demand. This allowed an intermediary comparison between the reference CAV system and the fully room-based demand controlled system.

Figure 15 shows the total primary energy consumption of the apartment when using each system type. All calculations used the primary factors stipulated in the Danish Building Regulations (BR18), with a value of 1.9 for fan power and 0.85 for district heating. Table 5 shows the CO_2 concentration in each supply room with each system. Applying a central VAV system yields substantial energy savings but at the cost of very poor IEQ in the bedrooms, with half of occupied hours providing CO_2 concentrations above 1200 ppm. Both room-based DCV systems yield exceptionally good IEQ in the bedrooms with much lower total energy consumption relative to the CAV system. It is worth noting that we did not take into account the extra pressure loss in the supply ducts from throttling the airflow with dampers when removing the air distribution box from the room-based DCV system. Furthermore, as noted in earlier sections, the air distribution box provides other benefits, such as an improved commissioning process and likely less noise.

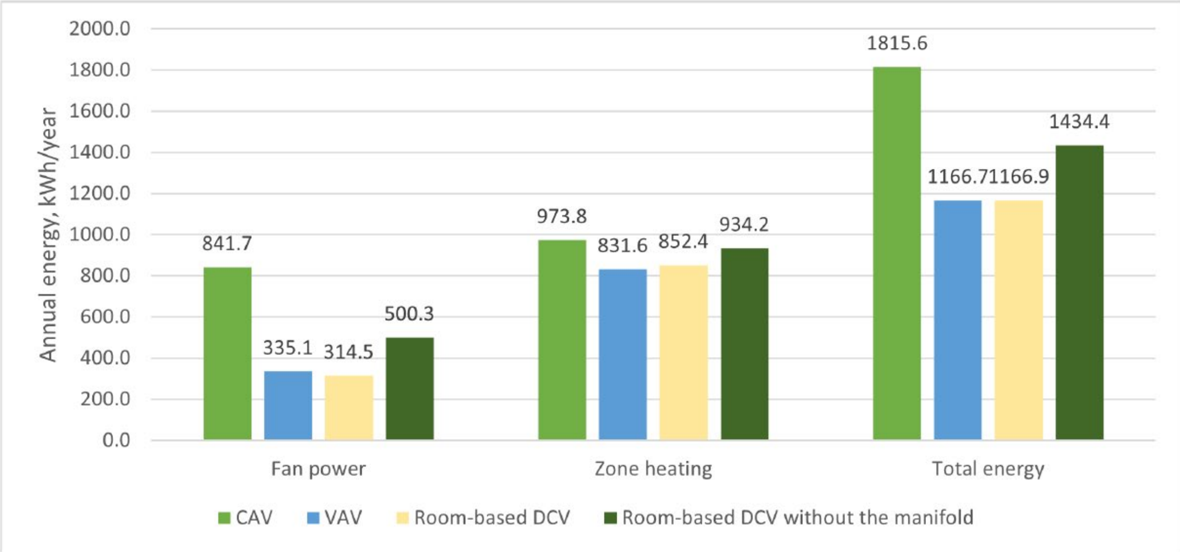


Figure 15. Simulated energy consumption of the analyzed ventilation systems.

Table 5. CO_2 concentrations in each supply room with the four different ventilation systems.

	Bedroom1	Bedroom2	Living room	Unit
CAV				
Duration of CO2 above 50ppm (Occupied)	1160	0	0	Hours
Ratio of occupied hours	31%	0	0	
Duration of CO2 above 1200ppm (Occupied)	0	0	0	Hours
Ratio of occupied hours	0	0	0	
Temperature and humidity controlled VAV				
Duration of CO2 above 950ppm (Occupied)	2580	314	507	Hours
Ratio of occupied hours	79%	10%	16%	
Duration of CO2 above 1200ppm (Occupied)	1640	0	13.3	Hours
Ratio of occupied hours	50%	0	0%	
Room-based DCV				
Duration of CO2 above 950ppm (Occupied)	0	0	0	Hours
Room-based DCV without the manifold				
Duration of CO2 above 950ppm (Occupied)	0	0	0	Hours

6.1.8 Experimental results

The clamp-on fan power meters only continued to operate in three apartments (i.e. one reference apartment and two with the novel system), as the gateway in one of the stairwells failed. Figure 16 shows the percentage year-over-year monthly AHU energy consumption, indicating monthly savings from 35-70%. The savings in August and September seemed reasonable due to the presence of open windows and sufficiently good IEQ based on measurements from indoor environmental quality (IEQ) measurement devices placed in each room.

However, the IEQ degraded somewhat in October and November, indicating that the algorithm did not effectively increase airflows during periods with high demand. Based on analysis of this limited timespan, it seemed that the control of the AHU required greater increases in airflows during these periods. We will modify and refine these controls in the months following completion of the project. As a result, the experimental results have yet to validate the savings indicated by the simulations while maintaining similarly high IEQ.

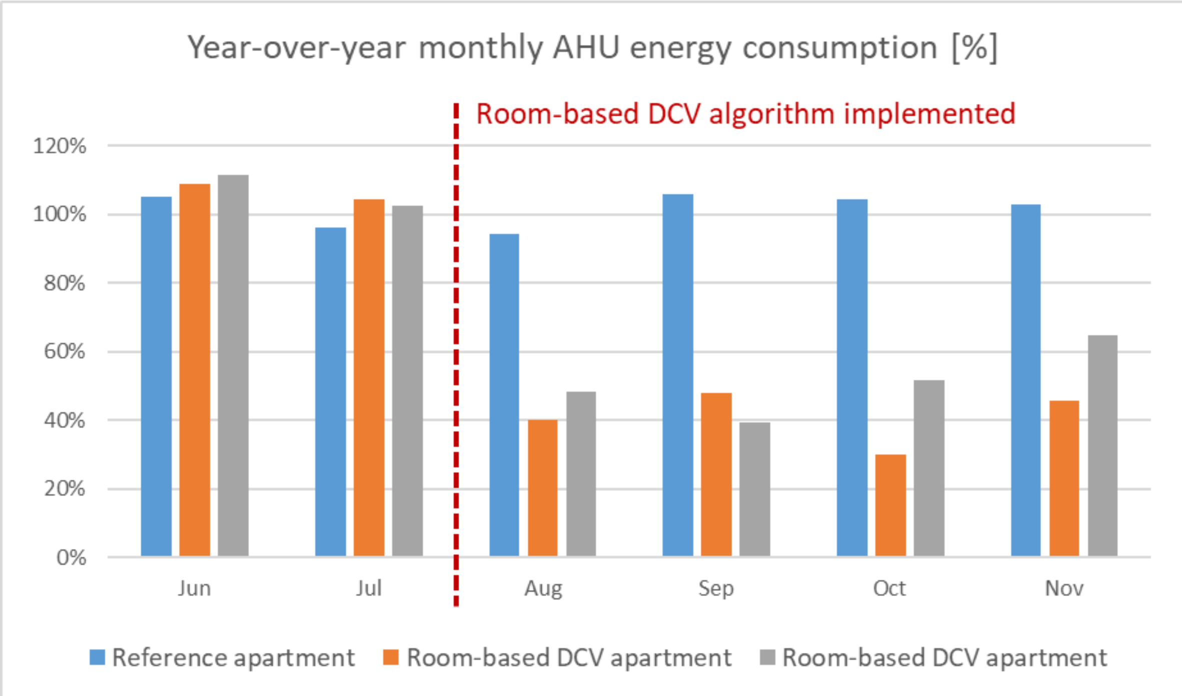


Figure 16. Monthly year-over-year AHU energy consumption depicting the energy use reduction after implementing the room-based demand-control algorithm in late-July, 2021; blue-reference apartment, orange and grey-apartments with advanced ventilation control.

It is important to note that these figures to do not include the fan energy used for the air distribution box. The recordings of these fan signals were intermittent, so we could only estimate their total use by prorating the consumption. These estimates use the fan affinity laws and assume a maximum fan power of 18 W at a fan signal of 10 V based on the datasheet provided by Ebm-Papst. Based on these estimates, the fan energy use by the air distribution box represents roughly 3% of the total.

6.1.9 Progress to the market

Ebm-papst is using the results from the current project for further optimization of the air distribution box. The second generation of the air distribution box is already in testing in Ebm-papst laboratory. It is close to the commercial version. Moreover, Ebm-papst has further versions planned already. Their progress is likely to be influenced by the results of the initial commercialized version. The project results directly dictated the main step in the optimization. They showed that pressure measurements in the distribution box were not as accurate as expected, so the compact fans were replaced with G3G133-R015-04 fans. The anemometers installed in these fans enable accurate control of the requested flow into each room, so there is no need to divide the air distribution box into separate chambers downstream of each fan (previously used to measure the differential pressure), simplifying the design. Thus, a redesign of the entire air distribution box was done. Several designs were tested before ending up with a more compact square version (Figure 17) more suited for the market.

Figure 17. Current prototype of the air distribution box in the Ebm-papst laboratory (left & middle), the expected final "square" design (right).

6.2 Continuous commissioning using 'smart ventilation' data

6.2.1 Developing a novel method for online continuous commissioning

Online connections can enable continuous commissioning of residential AHUs with heat recovery. We developed new methods using standard data from most AHUs with a parallel plate heat. This type of AHU represents the majority of residential AHUs with heat recovery on the market. The data typically includes temperature measurements and set points, fan signals and opening positions of valves and dampers. As Figure 18 shows, such temperatures are often labelled 'outdoor' (or 'outside'), extract (or 'room'), 'inlet' and 'exhaust'. If the AHU includes a heating or cooling coil, the data would include another temperature measurement before or after the coil on the supply side. The data typically shows the bypass damper position for the heat exchanger as well as the valve opening positon for the heating coil if one exists. With this data, one can estimate several performance indicators, such as the likely balance of airflows and the appropriateness of the supply air temperature set point, which controls the bypass of heat recovery.

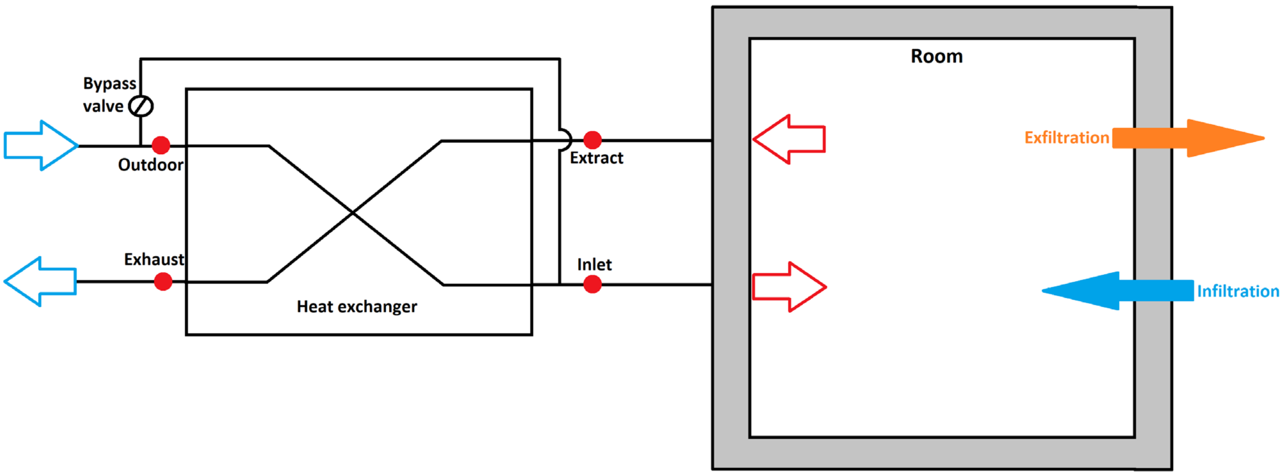


Figure 18. Commonly accessible data from a residential AHU with a plate heat exchanger that one can apply to continuous commissioning.

The first analysis concerns understanding of the control signals and regulation of the bypass damper, which generally has two main purposes. It helps avoid overheating in the apartment during the summer by partially bypassing heat recovery if the supply air temperature exceeds its set point. It also helps avoid freezing in the exhaust side of the heat exchanger when cooling the humid exhaust air to temperatures below 0 °C. Before applying physical analyses or indicators, one must ensure that the controller set points are appropriate and the data reflects the appropriate sensor measurements. This is a form a data cleaning and can reveal issues such as too-low supply temperature set points, causing excessive bypass of heat recovery, or sensor errors, such as improper installation or erroneous data logging.

As a starting point, we recommend analyzing the average position of the heat recovery bypass during the heating season to see if any AHUs are bypassing heat recovery excessively.

- If the bypass percentage is non-zero but still consistently low, it may be that the AHU is using a too-low supply air temperature set point, which could be increased. If the AHU uses a heating coil, one should not increase the supply-air temperature set point such that air heating increases significantly, as this could contribute unwanted heat.
- In cases of seemingly extreme bypass during the heating season, one should consider the extract temperature set point (also known as the cooling set point in AHUs without a cooling coil). Some AHUs bypass heat recovery for extract temperatures above a set point to avoid overheating. If the occupant's local heating set point exceeds the extract temperature set-point, the AHU will bypass heat recovery constantly, which is very poor outcome. To correct this, one can increase the extract temperature set point during the heating season to reduce unnecessary bypass. If this does not explain the high rate of bypass, one should look for a mechanical error, such as misplaced or faulty sensors or a stuck-open damper.

After cleaning the data and ensuring appropriate operation of the bypass damper for the heat exchanger, one can apply physical models to the data to analyze the performance of the ventilation system. One such indicator concerns the balance of the supply and exhaust airflows, as most building regulations require balanced airflows (i.e. $Q_{exhaust} = Q_{supply}$) to minimize heat loss and mold risk. While most large-scale AHUs measure airflows using pressure differential sensors across the inlet plates of each fan, most apartment-level AHUs to do not measure airflows. As described at the beginning of Section 6.2, commissioning of ventilation rates in residences is prone to error, which can result in severely unbalanced airflows. The proposed indicator seeks to detect the improper commissioning or maintenance of ventilation rates that cause large imbalances and excessive mechanically driven air leakages (i.e. infiltration or exfiltration).

As Equation 2 shows, if the supply and exhaust airflows are equal, the temperature increase in the supply air will equal the temperature decrease in the exhaust air. Further, it shows that the ratio of the temperature changes is inversely proportional to the ratio of mass flow rates, where T is temperature, $\dot{m}$ is mass flow, ρ is density and Q is airflow. Therefore, one can assess the balance of airflows ($Q_{exhaust}/Q_{supply}$) from the temperature changes of both airflows ($(T_{supply} - T_{outdoor})/(T_{indoor} - T_{exhaust})$). However, this is only true under certain conditions:

- When applying data filtering, the heat exchanger must show 0% bypass, meaning that none of the supply airflow bypasses the heat exchanger. Alternatively, one could filter for instances with active heating and an outdoor temperature above 0 °C, assuming this implies a closed bypass damper, but it would depend on well-functioning controls.
- Ideally, one should also filter for dry conditions inside the heat exchanger by comparing the temperature of the exhausted air to the dew-point temperature of the extracted air (based on measurements of temperature and relative humidity). Moisture in the exhaust air condenses in the heat exchanger if cooled below the air's dew point, so the extra heat negatively affects the accuracy of the indicator.
- One must assume that the difference in density between the supply and exhaust airflows is roughly negligible through the length of a modern high-efficiency heat exchanger due to the low temperature difference between them. Even in the worst case with no heat recovery, the dry air densities would likely deviate by less than 4% in the applicable temperature range (i.e. $1.00 < \rho_{outdoor}/\rho_{extract} < 1.04$).

When meeting these conditions, Equation 1 indicates the balance of ventilation airflows.

$$\frac{(T_{supply} - T_{outdoor})}{(T_{indoor} - T_{exhaust})} = \frac{\dot{m}_{exhaust}}{\dot{m}_{supply}} = \frac{\cancel{\rho_{exhaust}}}{\cancel{\rho_{supply}}} \cdot \left(\frac{Q_{exhaust}}{Q_{supply}}\right) = Capacity\ ratio, Cr \qquad (2)$$

When balancing the airflows, we need to adjust one of the fan signals. A fan's airflow is proportional to its speed (according to the fan affinity laws), and fan speeds for many fans are proportional to their fan signal. Therefore, balancing the airflows may be as simple as scaling the fan signals according to the ratio calculated in Equation 2.

There are two ways to balance out the airflows when one is less than the other. We can either scale up the smallest airflow or scale down the largest airflow. However, many apartment-level AHUs use variable-air-volumes (VAV), so they have a minimum ventilation rate that satisfies the minimum requirements in the building regulations and a maximum ventilation rate that satisfies the boost requirements for exhaust airflows in the regulations.

In developing a scaling method, we chose to scale down the minimum exhaust fan signal and scale up the maximum supply fan signal. Our reasoning involves several assumptions. When commissioning the system, the installer likely measured sufficient airflow into the supply terminals when setting the minimum fan signals for the supply, so we keep this constant. Similarly, they likely measured sufficient airflows for the exhaust intakes when setting the maximum exhaust fan speeds, so we keep these constant. Thus, we recommend adjusting the maximum supply fan signal and the minimum exhaust fan signal. In both cases, we must arrive at the same ratio for the minimum and maximum fan signals, as calculated by Equation 2.

Furthermore, this method is suitable for systems that have the following conditions:

- Underbalanced, where the ratio calculated by Equation 1 is between 0.6 and 0.9. In many cases, lower values would result in a scaling ratio becoming too large with new fan settings outside the 0-10 V limits.
- Mainly operating at the lower fan signals most of the time, so we can calculate an appropriate ratio.
- Do not already have a very low minimum fan setting for the extract fan, preventing lowering it further without nearing 0 V.

The fans could have a different imbalance at their minimum signals than at their maximum signals before applying the scaling. This is unavoidable unless the fan settings are close to identical for the supply and extract. Before applying the scaling method, it is necessary to check at which signals the fans mostly operate. It is important to note that this method only calculates the ratio between the supply and exhaust airflows, so the absolute ventilation rates are often unknown. However, adjusting the ventilation balance can result in substantial savings by reducing mechanically driven infiltration/exfiltration and maximizing total heat recovery.

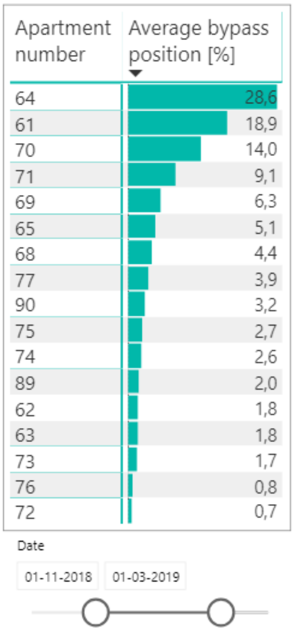
6.2.2 Applying the continuous commissioning method at Ryesgade 25

The demonstration case of the Ebm-papst air distribution box at Ryesgade 25 focused on eight specific apartments, but the entire apartment complex contained 42 units with 'smart' AHUs, allowing continuous commissioning of a broader sample within the project. The AHUs were connected to the internet via an Ethernet cable, and the data with 2-15 minute intervals was made available through the manufacturer's web portal. The ventilation units have been logging data since May 2018. The data included measurements of air temperatures before and after the heat exchanger in both airstreams, the relative humidity in the extract air and the position of the bypass damper. The AHUs did not have a heating or cooling coil.

We used the 'smart ventilation' data to visualize suitable indicators in Power BI and analyze the bypass damper regulation and fan signals. Our initial analysis included only 17 of the 42 apartments. We had observed that all apartments had high rates of bypass in the prior heating season, so we instructed the property manager to increase the supply temperature set points in all AHUs. This was an obvious measure as the excessive bypass contributed unnecessary heat loss, and the AHUs did not have a heating coil that could otherwise provide excessive air heating. While this helped, it did not solve the issue, as 12 of the 17 apartments had an average bypass position of 5.1% or less in the subsequent heating season, as shown by Figure 19, constructed in Power BI data visualization tool. Furthermore, four of the apartments had average bypass positions above 9%, which would warrant further inspection.

After observing the high rates of bypass in several of these 17 apartments, we decided to extend our analysis to all 42 apartments. This analysis revealed that four apartments had AHUs that were off for long periods. This should never be the case since the apartments could risk condensation and mold growth because of the humid air. We could not discern whether this was a technical fault or the occupants were able to turn off the AHUs using the circuit breaker or a vacation mode.

As Figure 20 shows, some apartments were almost fully bypassing the heat exchanger during the entire winter, exhausting air at room temperature instead of recovering its heat. The data in the figure shows only the winter months from 1/12/2019 to 1/3/2020, and it is clear that the difference is large between the apartments.



Apartment number	Average bypass position [%]
64	28,6
61	18,9
70	14,0
71	9,1
69	6,3
65	5,1
68	4,4
77	3,9
90	3,2
75	2,7
74	2,6
89	2,0
62	1,8
63	1,8
73	1,7
76	0,8
72	0,7

Date 01-11-2018 01-03-2019

Figure 19. Average bypass position from November to February in 17 AHUs.

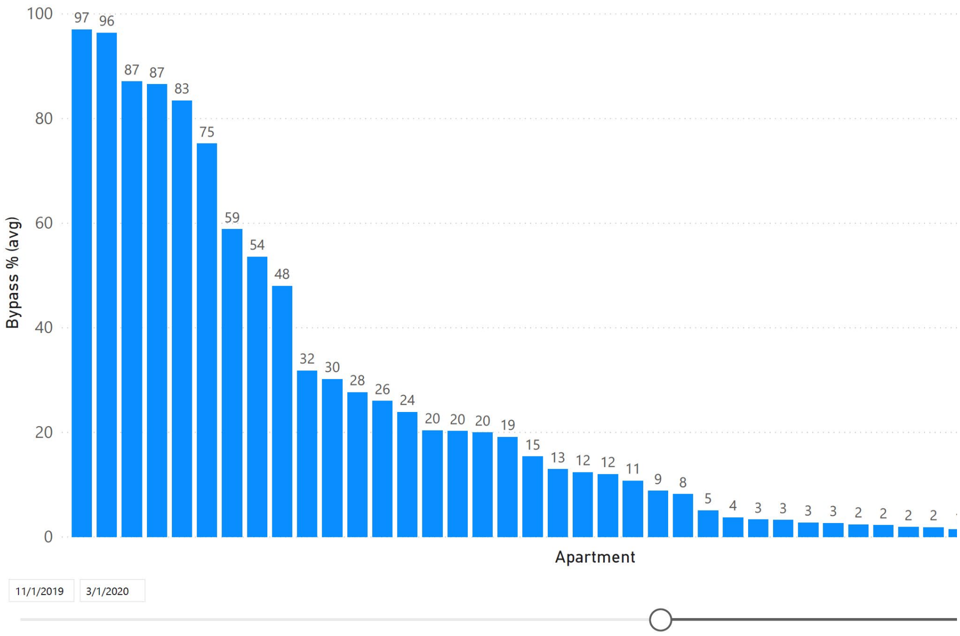


Figure 20. Average bypass percentage for each apartment in the winter period.

Figure 21 shows an overview of the operating status of the ventilation units in each apartment. Each apartment is assigned a color code. **Green** indicates that the unit works as expected (although heat recovery can be improved, see further in the text). **Red** indicates that the unit does not work as expected. **Black** indicates that the unit off for longer periods, which should never happen.

Opgang	Adress	Operation status	Notes
25	Ryesgade 25,		Turned off every night, Holidaymode during the day
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25,		Bypass signal not working (signal is always 0%)
	Ryesgade 25,		Bypass valve doesn't affect inlet temperature
25A	Ryesgade 25A,		
	Ryesgade 25A,		
	Ryesgade 25A,		
	Ryesgade 25A,		Bypass signal not working (signal is always 0%)
	Ryesgade 25A,		Bypass valve doesn't affect inlet temperature
25D	Ryesgade 25D,		
	Ryesgade 25D,		
	Ryesgade 25D,		
	Ryesgade 25D,		
	Ryesgade 25D,		
	Ryesgade 25D,		Turned off for long time periods

Opgang	Adress	Operation status	Notes
25B	Ryesgade 25B,		
	Ryesgade 25B,		
	Ryesgade 25B,		
	Ryesgade 25B,		Turned off for long time periods
	Ryesgade 25B,		
	Ryesgade 25B,		
	Ryesgade 25B,		Turned off for long time periods
	Ryesgade 25B,		
	Ryesgade 25B,		
	Ryesgade 25B,		
	Ryesgade 25B,		
25C	Ryesgade 25C,		
	Ryesgade 25C,		
	Ryesgade 25C,		
	Ryesgade 25C,		
	Ryesgade 25C,		
	Ryesgade 25C,		
	Ryesgade 25C,		Bypass valve doesn't affect inlet temperature
	Ryesgade 25C,		
	Ryesgade 25C,		
	Ryesgade 25C,		Bypass valve doesn't affect inlet temperature

Figure 21. Deeper analysis of the bypass operation in all 42 apartments. **Green** indicates that the unit works as expected (although heat recovery can be improved, see further in the text). **Red** indicates that the unit does not work as expected. **Black** indicates that the unit off for longer periods, which should never happen. Concrete addresses were covered by grey areas.

The results show that there are errors in the regulation of heat recovery bypass in the **red** apartments, which should only occur on warm days to avoid overheating in the apartments or on days with sub-zero outdoor temperatures to avoid frost accumulation in the exhaust side of the heat exchanger. In some of these apartments, however, the damper has been left 100% open for most of the winter, resulting in a large heat loss and thus energy waste. Initially, we suspected that the occupants were using higher heating set points for their radiators than the set-point for 'free cooling' in the AHUs. After inspecting the recorded data, it was clear that this was not the issue in the apartments with extreme bypass, as the room temperatures were within a normal range and would not have triggered constant 'free cooling' by bypassing heat recovery. Instead, we took a more detailed look at the regulation of the units using the data.

We inspected the time series data for many of the apartments. Figure 22 and Figure 23 show examples of well-functioning and poorly functioning supply air temperature controls, respectively, relating the bypass damper control to the supply air temperature. The former tracks the set point well by partially bypassing heat recovery, while the latter often fully bypasses heat recovery with seemingly no effect on the supply air temperature, which indicates a clear fault. We first suspected that the bypass dampers were stuck, but the bypass operation had a clear effect on the exhaust air, indicating that the bypass damper was functional. Strangely, the supply air temperature closely tracked the room temperatures, which implied that the sensor was actually in the room instead of the supply air duct where it should be.

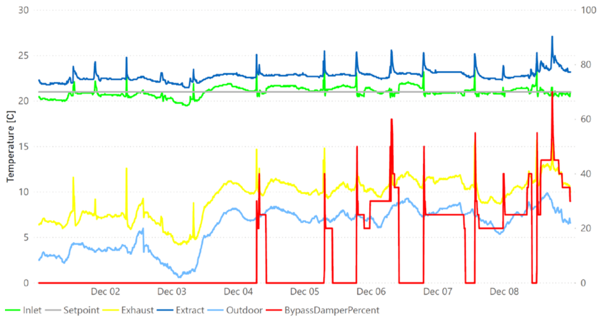


Figure 22. An example where heat recovery bypass (red) successfully controls the supply air temperature (green).

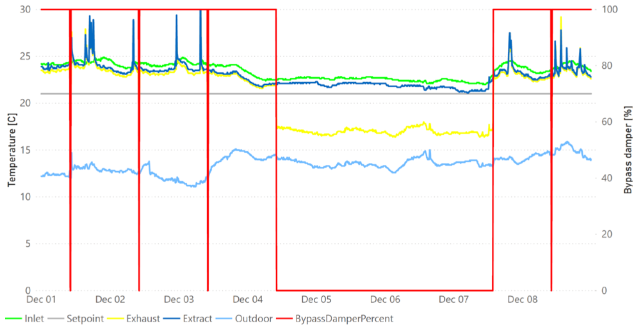


Figure 23. An example where heat recovery bypass (red) seems to have no effect on the supply air temperature (green) but a strong effect on the exhaust air temperature (yellow), indicating an error. Furthermore, the supply temperature closely tracks the room temperature (dark blue) instead of the set point (horizontal grey line).

The instructions for the AHU show that the installer must mount the supply-air temperature sensor in the supply duct, unlike the other temperature sensors, which are already mounted correctly inside the AHU in the factory. This provides an option to install an external post-heater. Figure 24 shows the guide for installing the sensor. Not mounting this sensor would leave it sitting in the room, measuring the incorrect values, potentially causing continuous bypass of the heat exchanger. Based on the data, an Airmaster representative agreed that this was likely the cause of the issue.

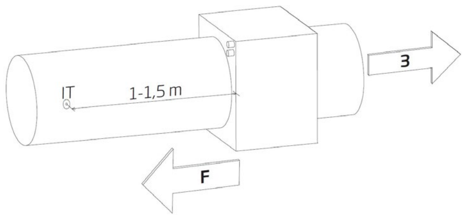


Figure 24. Installation instructions for the AHU showing placement of the supply temperature sensor.

As shown by Figure 21, an entire stairwell had the issue with constant bypass, so it was likely the same installer who forgot to mount the supply temperature sensors. This error resulted in complete bypass of heat recovery. Correcting this error should generate heat saving of up to 1500 kWh per apartment per heating season, so we recommended a technical visit to these apartments.

To calculate the indicator for balance of airflows, we first filtered the data for instances with a closed bypass damper, dry heat recovery, non-boosted ventilation rates and outdoor temperatures below 12°C. The chosen maximum outdoor temperature helps to ensure sufficient temperature differences to reduce the impact of sensor offset on the accuracy of the indicator while providing enough data for reliable analysis. Figure 25 shows the indicator for 17 apartments from 1/11/2018 to 1/3/2019, where 1.0 represents balanced airflows and less than 1.0 represents an undersupply of airflow. From an energy perspective, a slight undersupply of airflow may be reasonable since mechanically-driven infiltration partially offsets wind-driven infiltration. Furthermore, some error is expected from the commissioning process as well as measurement error. Therefore, the authors regard any value between 0.9 and 1.0 as satisfactory. Only four of the apartments had indicators in this range. Twelve of the apartments had indicators below 0.85, and four of these were 0.7 or less, which represented an airflow imbalance of at least 30%.

Apartment	Airflow balance
70	0,57
77	0,64
65	0,68
61	0,69
73	0,70
71	0,74
89	0,76
69	0,78
74	0,79
64	0,81
75	0,84
68	0,84
72	0,95
76	0,95
90	0,97
62	0,99
63	1,19

01-11-2018 01-03-2019

Figure 25. Airflow balance in 17 apartments based on the ratio of temperature changes in the AHUs.

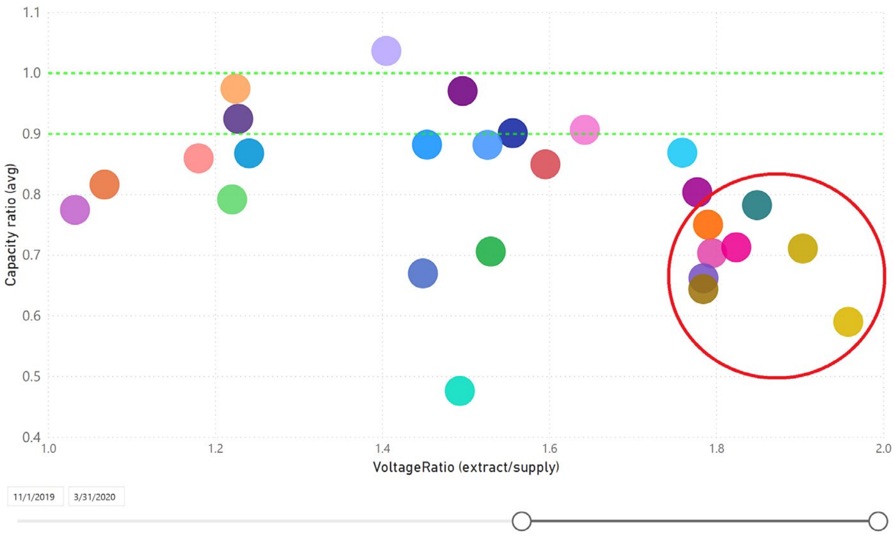


Figure 26. Visualization for detecting which apartments to apply the balancing method.

The results from the 17 apartments in the preliminary analysis led us to extend the analysis to all 42 apartments. Figure 26 shows all the relevant apartments with their extract/supply voltage ratio as well as the capacity ratio indicating the balance of airflows.

The apartments between the green dotted lines have a capacity ratio of 0.9-1.0, and we considered them balanced. However, the majority of the apartments were underbalanced. Where the voltage ratio was close to 1, the balancing method would not work well since the extract fan setting could not be scaled down without approaching 0 V. The apartments with a high voltage ratio (1.7-2.0) were more suitable for the scaling method because we could decrease the extract fan setting without approaching 0 V. Perhaps, one could scale up the supply airflows in these apartments, but we did not test this. The figure shows a group of suitable apartments in the lower-right corner where we could test the balancing method. After applying the balancing method, these apartments should have had a capacity ratio, Cr, between 0.9 and 1.0 due to the improved fan signals.

The AHUs vary ventilation rates according to the manual control panel and humidity-based DCV. The airflows typically vary throughout the day and season depending on several factors. Figure 27 shows typical distributions of airflow signals throughout the heating season after applying the same filters as the capacity ratio calculations. The signal remains at a lower level during the heating season, which is the main period of our focus due to impact of imbalanced airflows on infiltration heat losses.

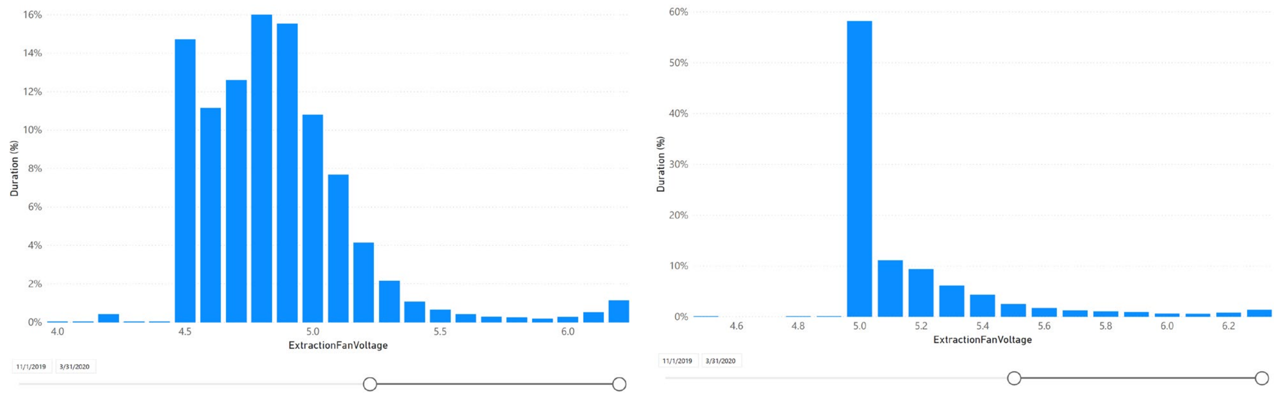


Figure 27. Airflow signal distributions for two apartments during the heating season, showing that the airflows are typically at lower level.

We balanced airflows in seven apartments with successful results. The outdoor temperature increased shortly after applying the new fan settings, such that the validation period was rather short for some apartments. However, the initial results were promising and indicated improved balance of supply and exhaust. Table 6 summarizes the capacity ratio improvement for each of the apartments and lists the number of valid measurements after the changes.

Table 6. The capacity ratio before and after applying the new fan settings. It includes the number of measurements used in the calculation.

	Capacity ratio before	Capacity ratio after	Number of measurements
C1	0.72	1.00	27
C5	0.79	0.95	45
C10	0.78	0.93	10
E0	0.78	0.97	300
E1	0.81	0.95	400
E2	0.70	1.00	530
E4	0.65	0.95	870

We will show the effects on apartment E1 and E4 in more detail since these are based on the most measurements and can bring insights into the performance before and after applying the new fan settings. Figure 28 shows the improved capacity ratio, indicating much better balance between supply and exhaust airflows. The measurement number on the horizontal axis shows how many measurements were made with the applied filters. In other words, all the data included in these figures are at instances with low outdoor temperatures and no bypass on the heat recovery. As the capacity ratio reflects the ratio of supply and exhaust temperature efficiencies, the increase in capacity ratio likely corresponded to an increase in total heat recovery.

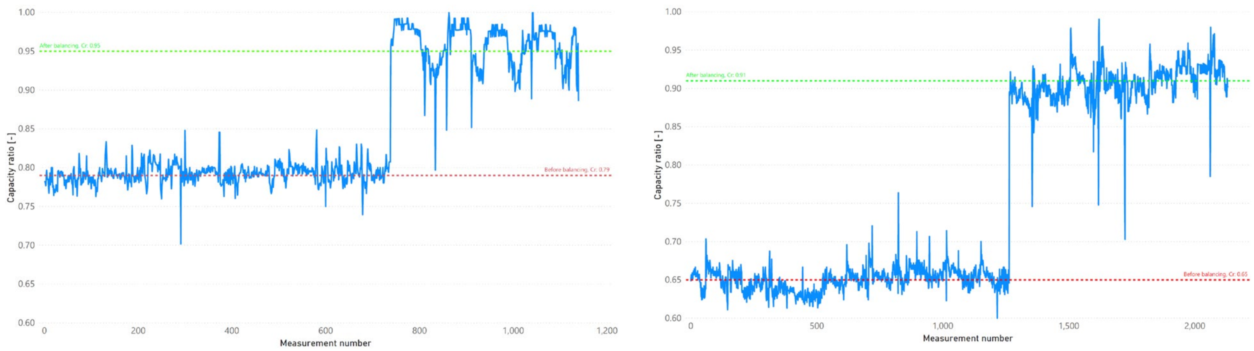


Figure 28. The capacity ratio of apartments E1 (left) and E4 (right) after applying the balancing method to the fans signals. The method was successful at increasing the capacity ratio to roughly 0.95, indicating much better balance of supply and exhaust.

6.3 Application of Metal Oxide Semiconductor (MOS) sensors

6.3.1 Usability of MOS VOC sensors for ventilation control

Metal Oxide Semiconductor (MOS) for measuring Volatile Organic Compounds (VOC) gain increasing attention because of their low price and possible ability to supplement or even substitute CO_2 sensors for demand-controlled ventilation (DCV). Nowadays, these sensors are used mainly in portable “Indoor Environmental Quality” meters working rather as smart home gadgets than ventilation control sensors. Amount of scientific studies focused on their reliability and applicability is still limited. These sensors seem to be an obvious step towards broadly available DCV[5]. They offer the possibility to account for pollution related to human presence as well as to indicate diverse odorous events. They are sensitive to a broad range of volatile compounds and trigger the ventilation also in the cases of emissions undetectable by standard CO_2 sensor. Secondly, MOS technology allows producing sensor units that are cheaper and less power demanding than current Non-dispersive infrared (NIDR) CO_2 sensors. These arguments speak for MOS VOC sensor technology. Nevertheless, there are also disadvantages. Recent research showed that simple replacement of CO_2 sensors with VOC sensors is not enough to achieve the desired effect[6,7]. A ventilation control strategy needs to be tuned specifically for use of VOC sensors so that their potential can be utilized. The broad sensitivity of the MOS VOC sensors, mentioned earlier as an advantage, turns out to be a disadvantage when issues like measurement accuracy and calibration are considered. Broad sensitivity is also a disadvantage if the sensors react to short-term “non-problematic” VOCs emissions like ethanol, perfume or limonene from oranges.

The motivation of research in the present project was that more rich and detailed information is needed to move MOS VOC sensors from being air quality indicators in cheap “home IEQ data loggers”, to be widely applied in residential ventilation. The goal was to provide scientific judgement regarding reliability of MOS VOC sensors for ventilation control by analyzing the response of commercially available MOS VOC sensors to pollutants emitted during activities typical for residences. Furthermore, the aim was to compare performance of commercially available MOS VOC sensors to the performance of the state of the art CO_2 sensor with respect to ventilation control.

[5] Herberger, S., Ulmer, H. (2012) Indoor Air Quality Monitoring Improving Air Quality Perception. Clean-Soil Air Water, 40 (6), 578-585.

[6] Kolarik, J. (2014) CO2 Sensor versus Volatile Organic Compounds (VOC) sensor – analysis of field measurements and implications for Demand Controlled Ventilation. In proceedings of Indoor Air 2014, Hong-Kong, China.

[7] Abdul-Hamid, A., El-Zoubi, S., Omid, S. (2014) Evaluation of set points for moisture supply and volatile organic compounds as controlling parameters for demand controlled ventilation in multifamily houses. In proceedings of Indoor Air 2014, Hong-Kong, China.

The experiments were conducted at a full-scale test room at Danish Technological Institute (Figure 29). Investigated activities included painting, cleaning, candle burning, emission of human bioeffluents, changes of relative air humidity, emission from linoleum flooring and dosing of ethanol into the test room.

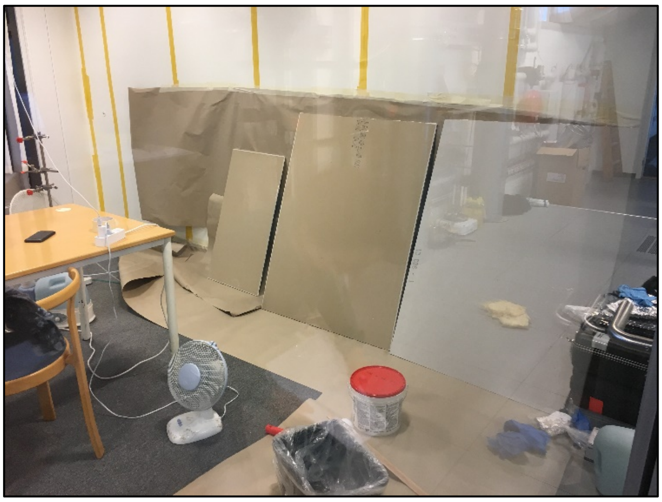



Figure 29. (left) Experimental set-up in the test room; in the middle a rack with linoleum flooring, to the right - Reaction-Time of Flight-Mass Spectrometer, to the left- rack with MOS VOC sensors; (right) preparation for condition "paining".

The screening of the market was conducted and seventeen potentially suitable sensors were identified. The final selection included commercially available sensors, in Table 7 abbreviated as A, B, C, D and E. Four of them were equipped with an embedded algorithm for so-called auto-calibration. The functionality of the algorithms was unknown as it is proprietary algorithm. However, a general functionality of auto-calibration is to utilize the lowest measured concentration over a longer period as a "clean air" baseline. A very precise analytical instrument - the Reaction-Time of Flight-Mass Spectrometer (PTR-ToF-MS) provided by Aarhus University was used as a reference measurement. This measurement was used to determine total concentration of VOC in the test room, so called TVOCPTR-TOF-MS as well as to measure a precise concentration of individual VOC compounds during the activities.

Table 7. Tested MOS VOC sensors

Producer	Model	Abbreviation	Standalone/ in casing	Approx. price in DKK (without delivery)
SGX Sensor-tech	MiCS-VZ-89TE	A	standalone	139,-
AMS	iAQ-Core C	B	standalone	148,-
Omelix	MQ-135	C	standalone	41,-
Siemens	QPA1000	E	in casing	1114,-
S+S Regel-technik	RLQ-W	D	in casing	1223,-

Results show that all pollution activities resulted in changes in the air quality that were detected by the MOS VOC sensors as well as the PTR-ToF-MS. Figure 30 shows an example of results for emission of human bioeffluents. It is clear that as soon as the experimental subjects entered the test room (at 10:00) the MOS VOC sensors started indicating the increase in bioeffluent concentration. The black like shows the reference measurement by PTR-ToF-MS. It can be seen that while the concentration patterns are rather similar, there is a difference in absolute concentration. This difference was observed among the sensor types, but also among specimen belonging to each sensor type.

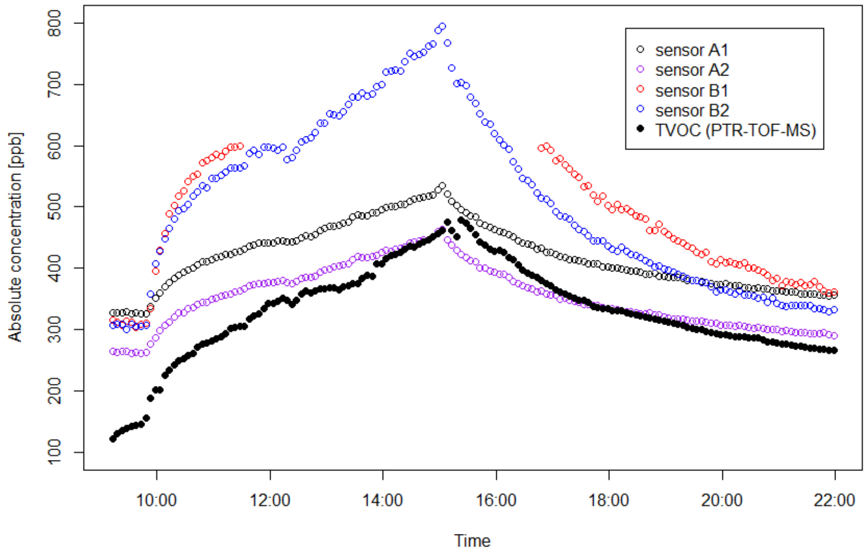


Figure 30. Absolute concentrations during exposure to human bioeffluents. The signal is incomplete for sensor B1 because the sensor was by mistake set to the low measuring range with upper border of 600 ppm.

The experiments showed that tested MOS VOC sensors were able to detect changes in VOC concentration during different pollution activities, but the measured signals differed in absolute values as well as in the amplitude of signal change. As documentation provided by manufacturers and suppliers was very limited regarding calibration and accuracy of the sensors, further testing is necessary to characterize performance of particular sensors. The results indicate that in order to use MOS VOC sensors for controlling ventilation, there is a need for further processing of the sensor signals. This processing should deal with the relative nature of the measurement. It can include either normalization with respect to minimum and maximum values for a particular measurement period or ensuring the proper functionality of the auto calibration algorithm. The fact that MOS VOC sensors cannot directly replace currently utilized CO_2 sensor indicated in previous research studies, seems to be confirmed also by the present study.

6.3.2 MOS VOC sensors' properties

Further analysis how to determine sensor properties like sensitivity or linearity. These properties are important when post-processing of the sensor signals is to be designed as well as to determine the suitability of particular sensors for concrete applications. In this report, data from the air polluting activity “Cleaning” will be used as an example to illustrate further analysis. As the partner aiming for integration of MOS VOC sensors in indoor climate measuring devices for ventilation control left the project consortium during the project, the findings from the experimental work has not been implemented in the practical control strategies.

Due to the operating principle of the MOS technology, the MOS VOC sensors provide a relative signal – a relative change of VOC concentration. Because of that, it is difficult to compare absolute values of concentrations measured by several sensors, even from the same producer. To deal with this problem, sensor signal data can be normalized, for example using mean concentration calculated using data for 3 hours before initiation of the polluting activity, or so-called min-max normalization known from the field of data mining.

Figure 31 shows the difference between absolute and normalized concentrations for the cleaning activity. The figure shows data for two specimens of two of the tested MOS VOC sensor types. The sensors produce signals of a similar pattern, but it can be clearly seen that absolute concentrations. When sensor signals were normalized by the background concentration obtained in the empty test room before the cleaning activity, the sensors produced signals that were comparable not only with respect to the pattern, but also the magnitude of the concentration change.

PTR-TOF-MS signal is depicted in the Figure 31 for comparison and it shows that the relative concentration indicated by the precise analytical instrument was slightly higher than the signals by MOS VOC sensors.

The challenges linked to the relative nature of the measurements are often addressed by using so called auto-calibration algorithms. They are proprietary, and producers do not disclose their exact functionality on the product data sheets. In general, the auto-calibration is supposed to ensure a “measurement baseline” determined using lowest measured concentration over certain (sufficiently long) period. Such approach assumes firstly, that sensor is activated in “clean air” conditions, secondly, that periods with “clean air” are ensured from time to time during the operational lifetime. If this is not fulfilled an inappropriate baseline can be established. The consequence is that some VOCs, especially those being constantly emitted from furniture, floor coverings, etc., are not detected. It is a building operator that needs to ensure that the sensors are regularly exposed to clean air.

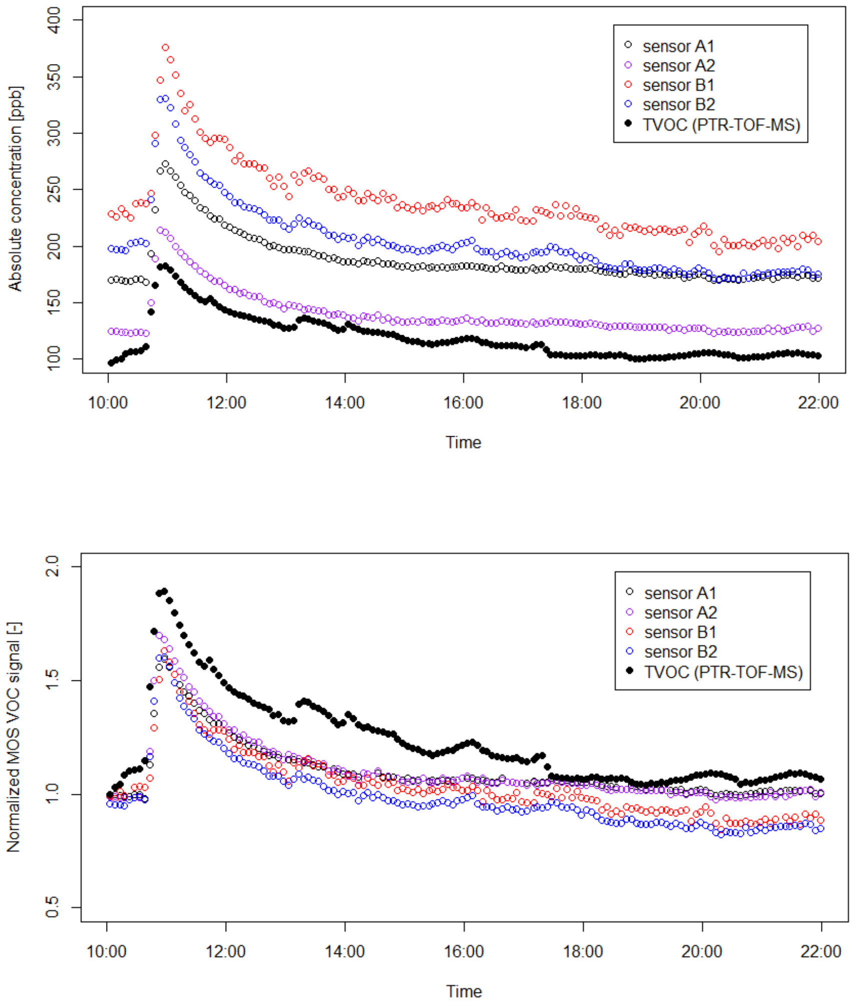


Figure 31. (top) Comparison of TVOC (PTR-TOF-MS) signal and absolute signal from two types of MOS VOC sensors (A and B) during cleaning activity, (bottom) normalized signal from two types of MOS VOC sensors; data from two specimens per MOS VOC sensor type are shown.

The results from the experiments with different pollution activities enabled to determine sensor properties like sensitivity or hysteresis. Sensitivity indicates how rapidly the sensor reacts to an increase in concentration respective to a reference measurement (being PTR-TOF-MS in the present project). Hysteresis indicates the difference in the sensor signal when the sensor is exposed to the same level of concentration during concentration build up and can delay respectively. The sensor properties were defined based on work by Fahlen et al.[8] Figure 32 shows a comparison of sensitivity for two studied MOS VOC sensors exposed to pollution activities cleaning, emission of bioeffluents and emission from linoleum.

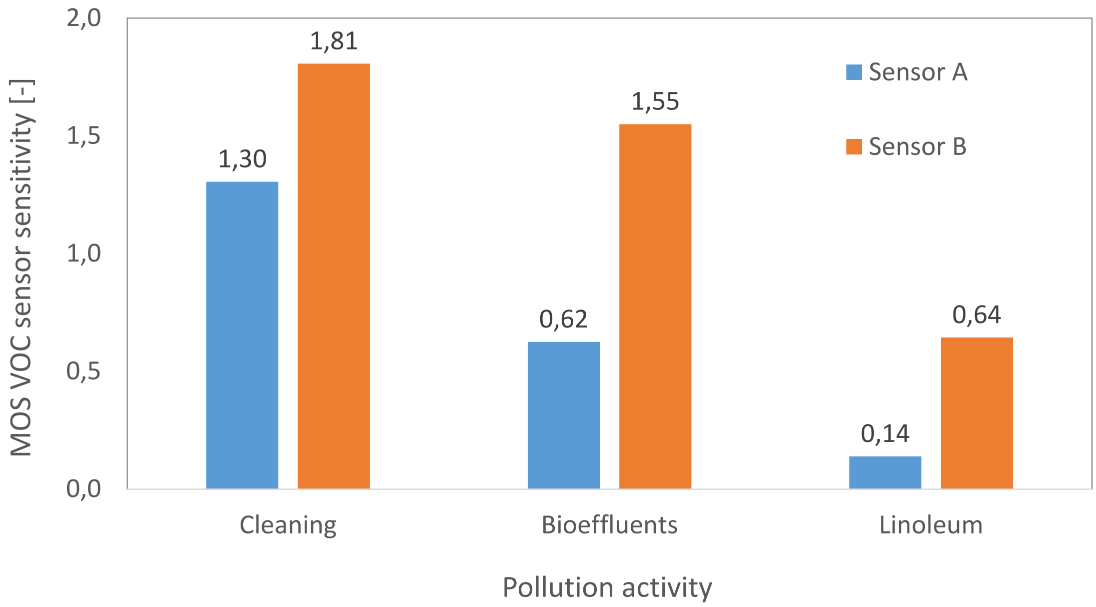


Figure 32. Comparison of MOS VOC sensors' sensitivity when exposed to cleaning, emission of bioeffluents and emission from linoleum.

The results show that the sensitivity differed among the pollution activities. It was highest during the cleaning activity and the second highest during emission to bioeffluents. Moreover, sensor B was in general more sensitive than sensor A. The differences in sensitivity for a particular sensor exposed to different pollution activities can be explained by the fact that different VOCs were emitted during the activities – see Figure 33. The presence of different compounds in resulting mixture had probably a different effect on the active layers of the MOS VOC sensors, which reacted differently to those chemicals. The experiment conducted within the project was not designed to analyze the undergoing mechanisms. The results however support practical observations that MOS VOC sensors react strongly to pollution generated by detergents, paints or human presence, while reaction to background pollution from building furnishing (like linoleum) is rather moderate.

In practice, the sensitivity of the sensor can help in the selection for an appropriate sensor with respect to its application. For example, if the sensor is supposed to account both for human occupancy and short-term pollution events like cleaning, sensor B seems to be more suitable, because its sensitivity to human generated pollution is comparable to the sensitivity to pollution from cleaning.

[8] Fahlen, P., Andersson, H., Ruud, S. (1992) Demand Control Ventilating Systems - Sensor Tests, SP Report 1992:13, Swedish National Testing and Research Institute, ISBN 91-7848

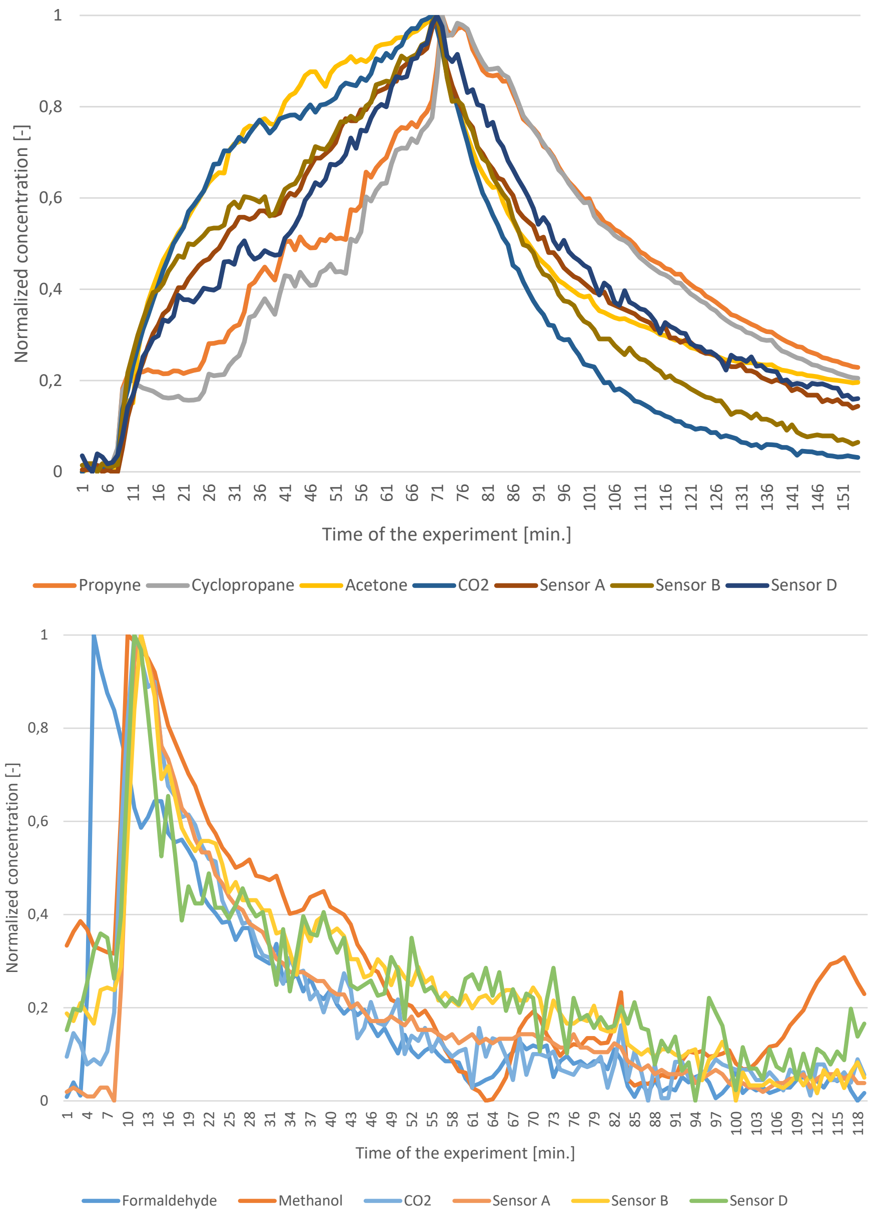


Figure 33. Normalized concentration of individual compounds with the contribution to TVOC (PTR-TOF-MS) > 5%, CO_2 concentration and signals from sensors A, B and D (top) emission of human bioeffluents, (bottom) cleaning.

6.3.3 Using MOS VOC sensors for ventilation control

However, the above-mentioned data do not provide any direst advice regarding ventilation control. More precisely, due to the need for normalization, it is very hard to establish limit concentration values corresponding to minimum and maximum airflow provided by ventilation system. This is illustrated in Figure 34.

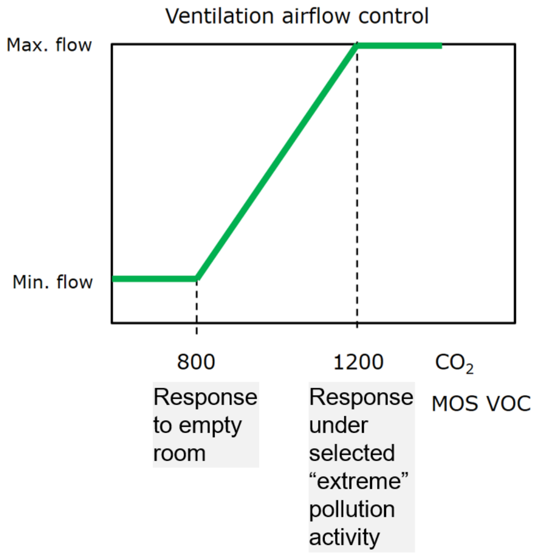


Figure 34. Establishing boundary values for minimum and maximum ventilation airflow using CO_2 and MOS VOC sensor signals.

The need for auto-calibration makes these sensors mainly useful for event detection. An option to determine limit concentrations for practical event based controls is using exposure to a pollution activity, during which the ventilation system must provide maximum available airflow. One example in residential setup could be painting or cleaning. The Figure 35 shows an example of such analysis. The exposure to painting is considered as a reference pollution event. The relative increase of the MOS VOC sensor signal is determined and this relative response is taken to result in demand for maximum airflow from the ventilation system. Consequently, the relative response to other pollution events (cleaning, bioeffluents, etc.) are expressed as a percentage of the maximum determined for painting.

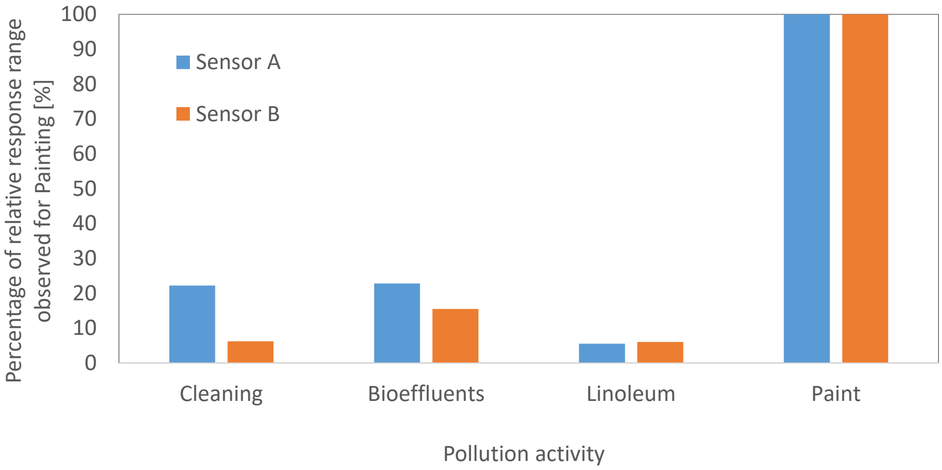


Figure 35. Percentage of relative response for sensor A and B calculated based on exposure to painting utilized during other tested activities.

It can be seen in the Figure 35, that there is a difference between the responses of sensor A and B to particular pollution activities. The relative increase of the signal from sensor A was higher than for sensor B for cleaning and bioeffluents. In these cases, using sensor A would lead to higher airflows than if the sensor B was used. In the case of linoleum pollution activity, the response of the sensor was comparable. It was not possible to apply the observed results in the project demonstration as the MOS VOC sensors were not integrated in the IC-Meter indoor climate loggers installed in demonstration apartments. The real life testing of the suggested approach remains therefore to be conducted in future projects.

6.4 Internet enabled communication of BREATHE 55 room ventilation units

Since the start of development phase of the BREATHE 55 room based ventilation unit, work has been done to enable wireless communication. However, there were uncertainties regarding the exact wireless technology to be used. The need for data transfer from and to the unit was not clear. In addition, at the start of the present project (2016) it was uncertain which technology would become the standard in the future (e.g. ZigBee, ZWave, LoRa, Wifi, Bluetooth, etc.). Therefore, it was chosen not to implement a wireless module in BREATHE 55 devices but instead have an open Modbus output, which will be compatible with the future chosen technology.

The current project aimed to test the wireless communication and uncover the need for how much and how fast data should be sent back and forth to the devices. The original plan was that Sustain Solutions was responsible for all the software and management challenges inside the devices to make the wireless control work, while IC-Meter was to handle the wireless communication from the devices and to the cloud. See Figure 36 for the principle drawing.

It turned out not to be possible for IC-Meter to deliver the wireless communication, so in order to communicate with the devices. Instead, it was chosen to establish a wired Modbus connection between each device and a central gateway placed in the test apartment, which would send data in the Cloud . Sustain Solutions took care of the expensive and not particularly aesthetic cabling of Modbus cables (Figure 37), while IC-Meter had to take care of the delivery of central communication units in the apartments, as well as getting the data in the cloud.

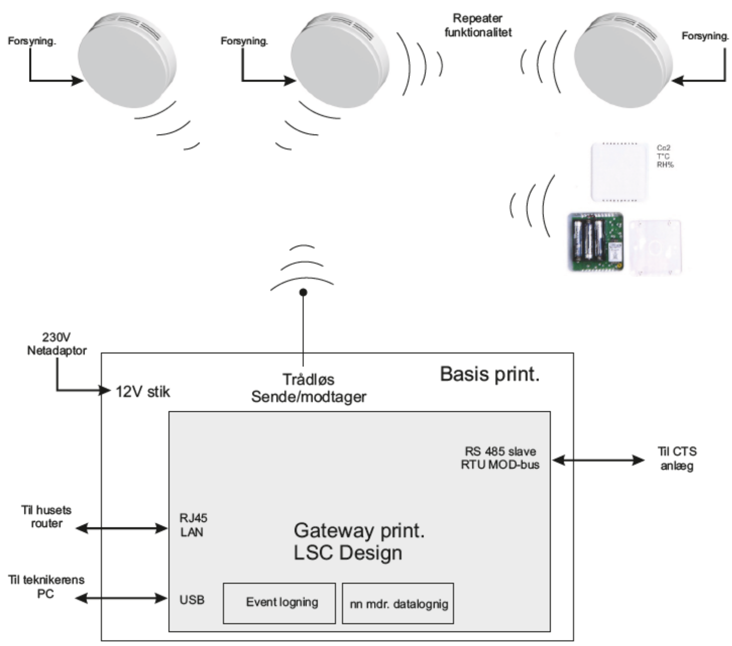


Figure 36. Principle sketch of wireless communication for BREATHE 55 devices. The drawing was made by Sustain Solutions electronics supplier LS Control, after IC-Meter could not handle this function.

Figure 37. Installed BREATHE 55 unit in test apartment with Modbus cabling. The Modbus cable must be removed and reassembled by filter replacement, which is not appropriate optimal for a standard installation.

The central communication was not delivered by IC-Meter, which withdrew from the project. Neogrid entered the project as a replacement for IC-Meter. Consequently, Neogrid and Sustain Solutions succeeded in installing suitable gateways and enabling data communication between the Cloud and eight BREATHE 55 units in the test apartments.

6.4.1 Online verification of the room-based demand control algorithm

The data allowed testing and verification of the BREATHE 55's novel room-based demand-control algorithm in an operational environment. The algorithm has three functional modes of operation: temperature control, humidity control and frost protection. All three control modes used sensors in the extract air to control the supply and exhaust fan speeds and the rotational speed of the rotary heat exchanger.

Figure 38 demonstrates the effective use of the temperature control mode, which adjusts the rotational speed of the heat exchanger to reduce heat recovery when it is not needed. If the temperature in the room rises above a cooling set point and the outdoor air is sufficiently cooler than the indoor air, the algorithm boosts the ventilation flow to provide free cooling. This intends to maintain low enough temperatures when the occupant cannot naturally ventilate (e.g. when the apartment is vacant during the day). However, we did not observe any instances where the controller boosted the airflow because the outdoor air was never sufficiently cooler than the indoor air (i.e. the apartments did not experience overheating due to solar radiation and high heat retention). The data at least verified that the heat recovery modulated correctly.

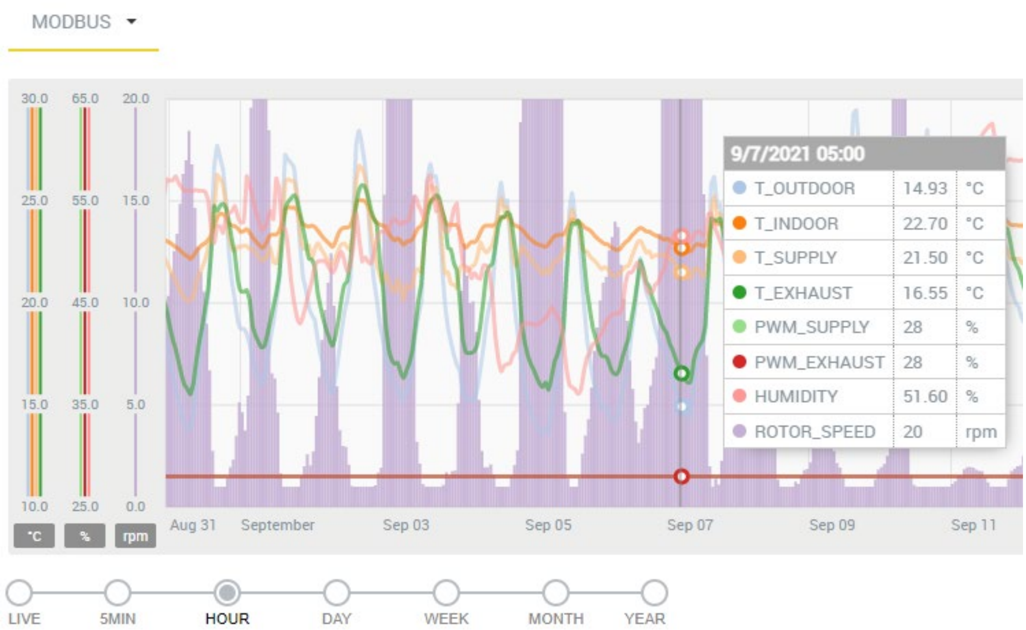


Figure 38. Demonstration of the temperature control mode of BREATHE 55 ventilation unit.

Figure 39 demonstrates a period with high relative humidity in a room served by a BREAHE 55 unit, which triggered the humidity control mode. Rotary heat exchangers transfer condensation from the exhaust side to the supply air, often maintaining high indoor humidity undesirably.

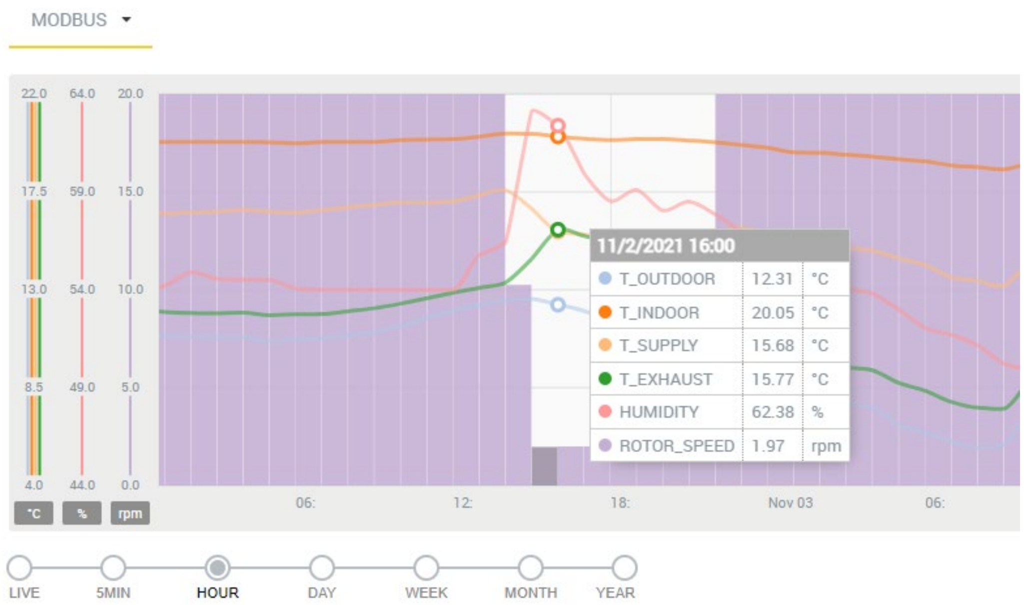


Figure 39. A sample visualization of sensor and control data from each BREATHE 55 unit, allowing verification of its novel room-based demand-controlled algorithm. The sample indicates that the controller responded correctly to high in-door relative humidity by reducing the coupled heat- and moisture-recovery.

As intended, the algorithm responded by reducing the rotational speed of the heat exchanger until the exhaust temperature rose above the indoor air's dew-point temperature. This minimized condensation inside the heat exchanger, thus limiting moisture recovery. As the figure indicates, the indoor humidity decreased in response. Once the indoor air was dry enough, the rotor increased speed to return to maximum heat recovery.

The data connection enabled a similar verification procedure for the frost protection mode, minimizing condensation inside the rotor when outdoor temperatures decrease below freezing. In such conditions, the unit turns off if it cannot maintain comfortable supply air temperatures while minimizing condensation in the rotor. As Figure 40 shows, the monitored data from the BREATHE 55 units revealed an error in the control code that prevented a return to normal operation after exiting the frost protection mode. The unit correctly entered frost protection mode and decreased heat recovery to minimize condensation in the rotor (negating any chance of frost accumulation). However, it could not simultaneously maintain sufficiently high supply air temperatures for comfort, so it turned off for a period of 3 hours, as the algorithm intended. Upon exiting frost protection mode, the operation continued as usual, except the fans signals remained at 0%, indicating an apparent error in the control code requiring an update to be fixed.

Figure 40. Visualization of the sensor and control data from a BREATHE 55 unit revealing an error in the control code upon exiting the frost protection mode. The unit decreased heat recovery to limit condensation in the rotor but could not maintain comfortable supply temperatures, so it turned off. The fan signals remained at 0% when it restarted until the user manually increased them.

6.4.2 Simulating realistic performance of room-based ventilation units

The article that serves as the basis for this section[9] was published in the journal *Energy and Buildings*.

Room ventilation units (RVUs) with heat recovery, like the BREATHE 55, offer an alternative solution for renovated residential buildings, allowing simple installation through the façade. However, wind can have a substantial impact on their performance, affecting the balance of airflows. Such imbalances between supply and exhaust negatively affect supply air temperatures and total heat recovery. Furthermore, the pressures caused by the stack effect in apartments with an exhaust ventilation shaft can have a strong negative influence on the performance of RVUs.

We performed a comprehensive simulation study to investigate these issues in relation to the fan type and operating point. This work aimed to predict the real performance of the BREATHE 55 and other RVUs in Danish apartments to assist the technical and financial feasibility analyses driving future investment. The study simulated the performance of RVUs in a typical Danish test apartment, located on the ground level, under various typical wind pressure conditions. To investigate the combined impacts of wind and stack effect, we simulated an apartment on the ground floor of a 4-storey building with an 11-meter natural ventilation shaft. We performed

[9] Filis, V., Kolarik, J., & Smith, K. M. (2021). The impact of wind pressure and stack effect on the performance of room ventilation units with heat recovery. Energy and Buildings, 234, 110689. https://doi.org/10.1016/j.enbuild.2020.110689

dynamic simulations with different fan characteristic curves and operating points for both centrifugal and axial fans due to their different performance levels when facing counter-pressures. Figure 41 shows an overview of the investigated parameters.

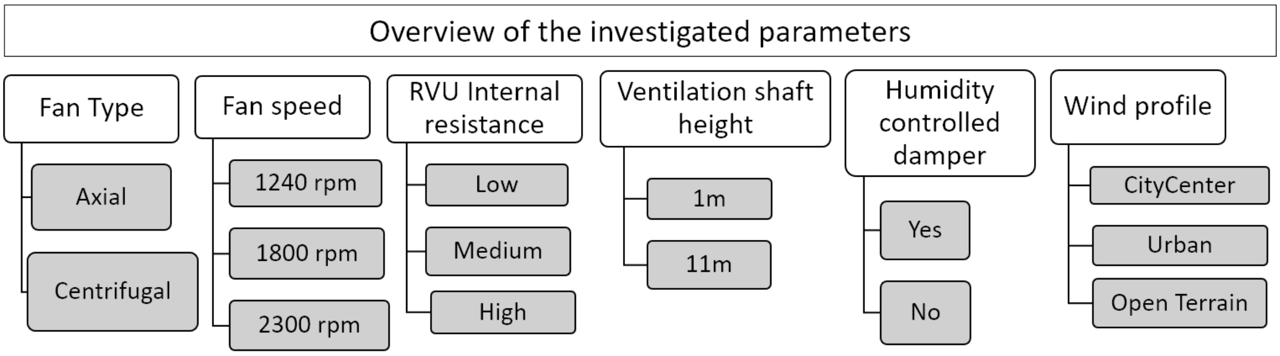


Figure 41. The investigated parameters in a simulation study of RVUs subjected to wind and stack effects.

The results showed that centrifugal fans, like the used in the BREATHE 55 unit, performed far better than axial fans (commonly used in most RVUs) because their steeper fan curves and generally higher operating pressures made them less sensitive to pressure differences. Thus, an RVU with a centrifugal fan is likely to provide more balanced airflows and greater total heat recovery, as shown in Figure 42.

When taking into account wind pressure and disregarding stack effect, the sensible heat recovery decreased by up to 8% in RVUs with centrifugal fans. Comparatively, at the same airflow setting, the sensible heat recovery decreased by up to 22% in RVUs with axial fans. After including stack effect, the decrease in sensible heat recovery was instead up to 20% for RVUs with centrifugal fans and up to 52% for RVUs with axial fans. Figure 43 shows the decrease in sensible heat recovery for these cases when subjected to wind and stack effect.

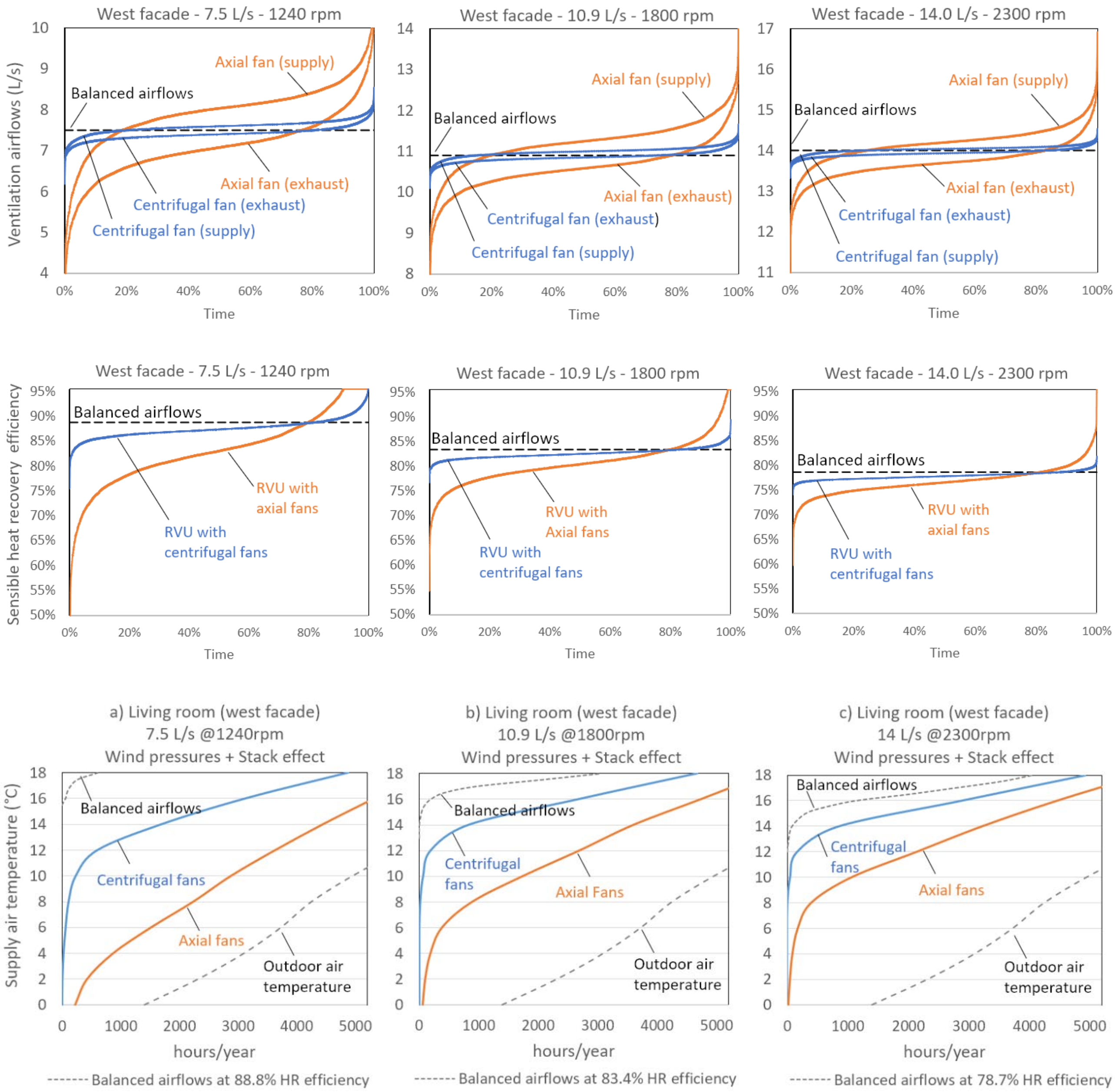


Figure 42. Impact of wind-driven pressure under an urban wind profile on the ventilation airflows (top), heat recovery (middle) and supply temperatures (bottom) in RVUs with axial or centrifugal fans at three fan different operating points.

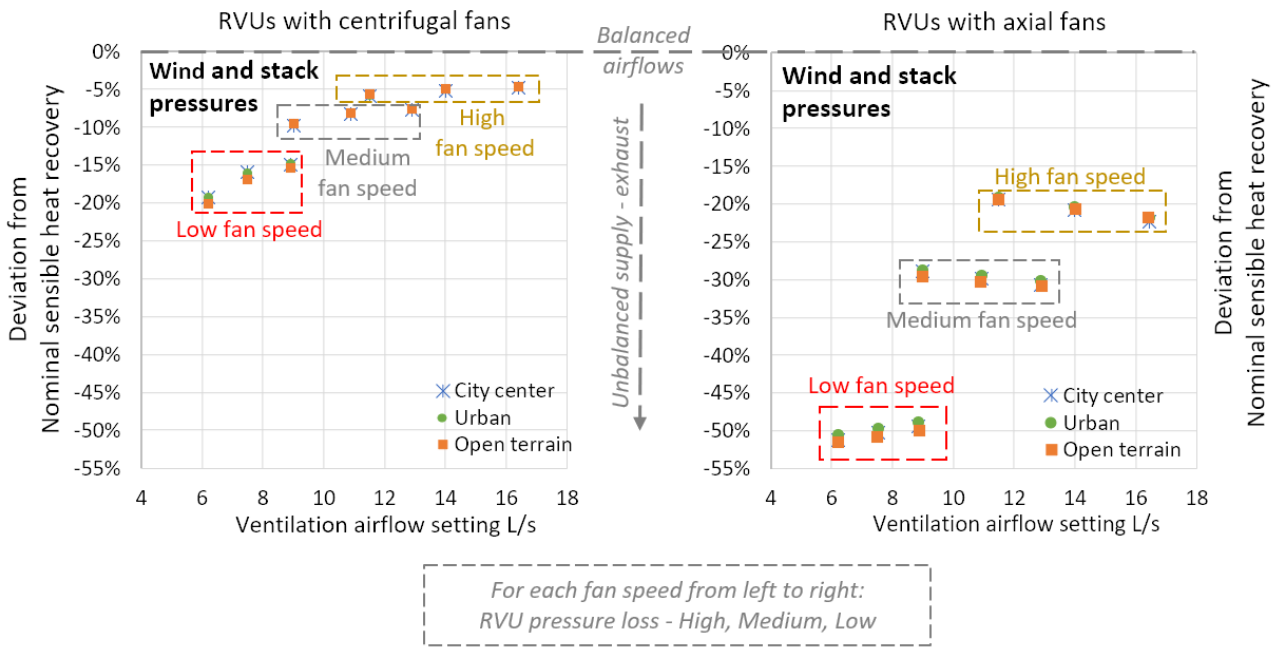


Figure 43. Reductions in total sensible heat recovery from nominal values due to wind and stack pressures under various wind profiles for RVUs with either centrifugal fans (left) or axial fans (right). Each graph presents results for both units, placed in west and east façade of the ground floor apartment.

To mitigate the impact of stack effect on the performance of RVUs, we proposed using a humidity-controlled damper in the intake to the natural ventilation shaft to reduce the pressure differences across the building envelope. We used the software IDA-ICE to simulate its impact. The inclusion of a humidity-controlled damper reduced the pressure differences due to stack effect and halved the negative impact on sensible heat recovery on average. Figure 44 shows that, as a result of the humidity-controlled damper, the RVUs were able to provide considerably higher supply air temperatures.

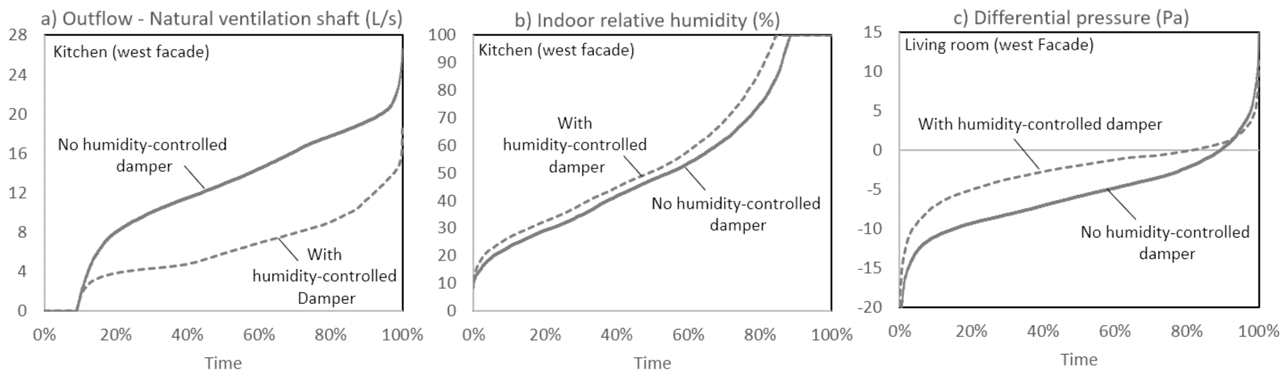


Figure 44. Impact of the humidity-controlled damper on the (a) outflow from the shaft, (b) indoor RH% in the kitchen, and (c) pressure difference across the west façade in the living room.

The investigation showed that a humidity-controlled damper could reduce the negative impact of stack effect on the performance of an RVU. Thus, those installing RVUs such as the BREATHE 55 should consider including such a humidity-controlled damper if the apartments have natural stack ventilation.

6.5 Target group and benefits of the project

The technological solutions developed in the project are targeted towards *building administrators* and *building owners* – rather housing associations than private owners - who seek solutions for efficient ventilation in renovated apartment buildings. Furthermore, also *engineers* and *contractors* as well as tenants will benefit from the project. This chapter summarizes the benefits, which the project brings to particular stakeholders. It needs to be mentioned that due to a limited demonstration period, it was not always possible to clearly demonstrate all the benefits. This was caused mainly by different technological problems that needed to be resolved in the demonstration apartments.

Building administrators can utilize results of the project to get overview about the performance of ventilation systems in buildings they manage. Possibility to get general overview about performance is a standard practice in office buildings, but it is seldom in apartment buildings with decentralized ventilation. Internet connected control and monitoring ventilation offers the building administrator possibility to monitor whether all systems are in operation according to required set points. Additionally, it also provides indication of those ones that operate inefficiently. The results of the projects show, that it is possible to detect ventilation units with unbalanced airflows as well as faulty installation of sensors. This gives a *building administrator* a powerful tool to ensure that decentralized systems deliver the desired indoor environmental quality to the occupants. The possibility for performance monitoring is the common denominator connecting all technologies developed within the project.

Building owners can renovate their buildings using easy to install room based ventilation units- BREATHE 55 that provide efficient room-based ventilation in buildings where an installation of standard ventilation solutions is impossible due to the lack of space or other reasons. On the other hand, the solution with air distribution box from Ebm-papst represents an improvement of standard decentralized ventilation system offering efficient air distribution into particular rooms according to their demand while decreasing energy use. The ability to monitor the systems during their lifetime and therefore ensure the agreed upon performance is an important benefit for the *building owners*.

Tenants have two main benefits. The first relates to the aforementioned ability to ensure performance. More precisely this means reduced energy bill while maintaining required indoor climate. The results mentioned in previous chapters clearly show the energy saving potential of the solutions; however, the limited demonstration period did not allow fine tune the systems to obtain exactly the same quality of indoor environment. Therefore, one can expect that the real energy savings will be slightly lower than obtained during the demonstration period.

Engineers and contractors will benefit from the results of computer simulations conducted within the project as well as from the results obtained during laboratory experiments with MOS VOC sensors. The simulations of room-based ventilation systems illustrate how the room based systems can be influenced by factors like wind pressure or position of the apartment in the building. Additionally the results demonstrate that selection of the fan type is another important parameter, which influences the performance of the whole system. *Engineers and contractors* can use the results during the design phase as well as select the right products to be installed.

6.6 Dissemination

The dissemination in the project was directed both towards practitioners as well as scientists. The important part of the dissemination towards practice will be a project seminar, which, due to previously described changes and delays in the project, will take place first after finalization of the project - in February 2022.

The substantial part of the project dissemination took place within the framework of the project under International Energy Agency- IEA EBC Annex 68 - Indoor Air Quality Design and Control in Low Energy Residential Buildings (www.iea-ebc-annex68.org). This created a platform for sharing experiences on both national and international level. The dissemination included presentation of the project at Annex 68 meetings, which, besides the scientific experts, were also attended by designers and other stakeholders involved in residential ventilation. As the meetings took place not only in Denmark, but also in other European countries as well as in the USA and China, the project receiver the international audience.

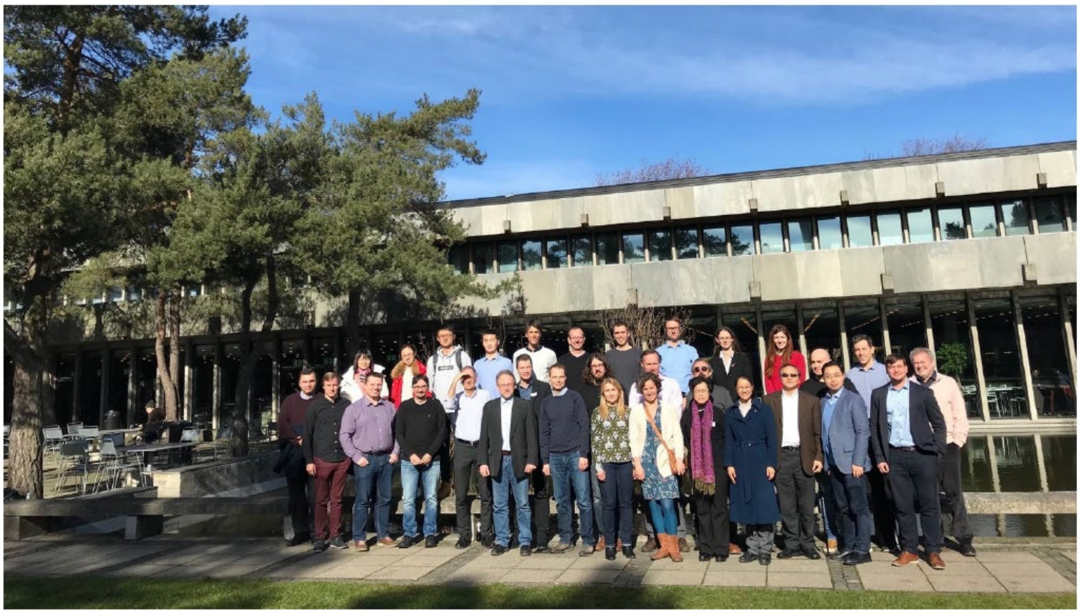


Figure 45. Participants at IEA EBC Annex 68 meeting at DTU, Denmark in March 2019.

Moreover, the results regarding experimental work on MOS VOC air quality sensors were presented at a webinar organized in cooperation with Air Infiltration and Ventilation Centre (AIVC, www.AIVC.org). Not only the audience of nearly 90 participated at the webinar, but also the recording and presentation materials are available for stakeholders worldwide on AIVC’s webpage. The Table 8 summarizes the dissemination within the project.

Table 8. Dissemination summary.

	Title/ reference	Publication type
01	Kolarik, J. (2021). Experience with Low-cost (MOS VOC) sensors – response to typical pollution activities and suitability for demand control in residential ventilation. Online seminar, bauinformation.com, 20.1.2021	Seminar for Austrian stakeholders
02	Filis, V., Kolarik, J., & Smith, K. M. (2021). The impact of wind pressure and stack effect on the performance of room ventilation units with heat recovery. Energy and Buildings, 234, [110689]. https://doi.org/10.1016/j.enbuild.2020.110689	Journal article
03	Kolarik, J. (2020). Properties of MOS VOC sensors and their suitability for ventilation control. Seminar for sponsors of the International Centre for Indoor Environment and Energy, DTU Byg, 8.9.2020	Seminar for Danish stakeholders
04	Kolarik, J. (2020). MOS VOC IAQ sensorer – Kan alle måle luftkvalitet med tilstrækkelig kvalitet? EUDP & DANVAK Online seminar om Ventilation, Indeklima og Energi, 1.10.2020	Seminar for Danish stakeholders
05	Kolarik, J., Lyng, N. L., & Laverge, J. (2020). Metal Oxide Semiconductor sensors to measure Volatile Organic Compounds for ventilation control. Report from the AIVC Webinar: "Using Metal Oxide Semiconductor (MOS) sensors to measure Volatile Organic Compounds (VOC) for ventilation control", held on September 4, 2018	Report for Air Infiltration and Ventilation Centre
06	Smith, K. M., & Kolarik, J. (2019). Simulations of a novel demand-controlled room-based ventilation system for renovated apartments. I O P Conference Series: Materials Science and Engineering, 609(3), [032041]. https://doi.org/10.1088/1757-899X/609/3/032041	Conference article
07	Smith, K. M. (2019). Modelling room-based residential ventilation. IEA EBC Annex 68 expert meeting, 11.3.2019, Copenhagen, Denmark	Presentation at Annex 68 expert meeting
08	Bossi, R., Kolarik, J., Wargocki, P., Lyng, N.L., Witterseh, T., Skov, H. (2019) Chemical characterization of volatile organic compounds emitted from selected indoor activities. 8th International PTR-MS Conference 2019 University of Innsbruck, Innsbruck, Tirol, Austria	Presentation at conference
09	Smith, K. M. (2018). Room-based demand-control of residential ventilation in IDA-ICE. Equa Power Days, Solna, Sweden	Seminar by Equa Simulation AB
10	Smith, K. M. (2018). Room-based demand-control of residential ventilation. IEA EBC Annex 68 expert meeting, 27.9.2018, Syracuse, NY, USA	Presentation at Annex 68 expert meeting
11	AIVC Webinar (2018). Using Metal Oxide Semiconductor (MOS) sensors to measure Volatile Organic Compounds (VOC) for ventilation control: https://www.aivc.org/event/4-september-2018-webinar-using-metal-oxide-semiconductor-mos-sensors-measure-volatile-organic	Webinar organized for AIVC
12	Smith, K. M. (2018). Demand based control of innovative decentralized ventilation system installed in renovated apartment building – update from RoomVent Solutions project. IEA EBC Annex 68 expert meeting, 25.3.2018, Shanghai, China	Presentation at Annex 68 expert meeting
13	Kolarik, J., Wargocki, P., Smith, K. M., Lyng, N.L., Witterseh, T., Bossi, R. (2018) Performance of MOS VOC sensors tested under activities typical for residences- a research update from RoomVent Solutions project. IEA EBC Annex 68 expert meeting, 25.3.2018, Shanghai, China	Presentation at Annex 68 expert meeting
14	Kolarik, J. (2017). System solutions for demand-control and continuous-commissioning of room-based ventilation in dwellings. IEA EBC Annex 68 expert meeting, 21.3.2017, Dresden, Germany	Presentation at Annex 68 expert meeting
15	Kolarik, J., Wargocki, P., Smith, K. M., Lyng, N.L., Witterseh, Bossi, R., Li, R. (unpublished) Using Cluster Analysis to the determine performance of low-cost MOS VOC sensors	Manuscript in preparation
16	System solutions for demand-control and continuous-commissioning of room-based ventilation in dwellings – results and experiences from the project	Final seminar in preparation
17	Kolarik, J., Lyng, N.L., Bossi, R., Witterseh, T., Smith, K. M., Wargocki, P. (2020) Response of commercially available Metal Oxide Semiconductor Sensors under air polluting activities typical for residences. In: Indoor Air Quality Design and Control in Low-Energy Residential Buildings (EBC Annex 68); Subtask 4: Current challenges, selected case studies and innovative solutions covering indoor air quality, ventilation design and control in residences. AIVC Contributed Report 19, INIVE EEIG, Sint-Stevens-Woluwe, Belgium, ISBN 2-930471-58-7	Chapter in a AIVC contributed report
18	Smith, K. M., Kolarik, J. (2020) Design of room-based ventilation systems in renovated apartments. In: Indoor Air Quality Design and Control in Low-Energy Residential Buildings (EBC Annex 68); Subtask 4: Current challenges, selected case studies and innovative solutions covering indoor air quality, ventilation design and control in residences. AIVC Contributed Report 19, INIVE EEIG, Sint-Stevens-Woluwe, Belgium, ISBN 2-930471-58-7	Chapter in a AIVC contributed report
19	Smith, K. M., Anker Hviid, Ch., Kolarik, J. (2020) Continuous-commissioning of ventilation units in multi-family dwellings using controller data. In: Indoor Air Quality Design and Control in Low-Energy Residential Buildings (EBC Annex 68); Subtask 4: Current chal-lenges, selected case studies and innovative solutions covering indoor air quality, ventilation design and control in resi-dences. AIVC Contributed Report 19, INIVE EEIG, Sint-Stevens-Woluwe, Belgium, ISBN 2-930471-58-7	Chapter in a AIVC contributed report

7. Utilization of project results

Despite the fact that *Sustain Solutions* did not managed to realize the plan for wirelessly connected BREATHE 55 units within the project, the realized demonstration brought important insights into the functionality and operational robustness of the room based ventilation units. The possibility for monitoring of the units, although via Modbus, gave a possibility to study behavior of the control algorithm in real life. In the meantime, Sustain Solutions decided to sell the product – BREATHE 55 to another commercial partner, so it will be marketed and further developed by another company. This is due to reorganization of the Sustain Solutions' product portfolio. However, based on the experience from the project, Sustain Solutions clearly recognize the advantage and necessity of online monitoring. For the future of the product, Sustain Solution sees the necessity of the wireless control possibility for the product. Not only because of the obvious technological advantage, but also because the competitors on the market offer this possibility, despite the fact that actual performance of their ventilation solutions does not reach the level of BREATHE 55. The ongoing commissioning is a clear advantage, especially when room based units are installed in social housing or similar types of buildings. Despite the fact that Sustain Solutions did not managed to develop the financial model for room based ventilation in residences within the present project, it is clear that obtained results enable an easy demonstration of advantages of residential ventilation.

Ebm-papst is already directly using the results from the project for further optimization of the air distribution box. The second generation of the air distribution box is already in testing in Ebm-papst laboratory and should be released in 2022. Ebm-papst closely considers IoT integration of their solution, however this part of the development will be realized by the internal control and monitoring department and not in collaboration with external partners like in the present project. According to Ebm-papst the results of the project clearly showed the high potential of air distribution box, but also pointed out technical issues that needed to be addressed in the next version. Ebm-papst's vision is a system that needs a minimum commissioning after installation, because it can be "pre-commissioned" in the factory. The future development will focus on the optimization of the air distribution box for the air supply. Moreover, the corresponding version of the device to be installed in the exhaust part of the system is also planned. This would enable changing the extracted air ration between kitchen and bathroom, eventually among more spaces (e.g. second toilet, utility room etc.). The possibility for embedded control in the air distribution, in comparison to the current solution where the control logic is provided by the external controlled, remains an unsolved question and will be addressed based on the commercial results from the near future.

For *Neogrid Technologies*, the project has brought an improved perspective on ventilation control and monitoring. Although its project focus has been on supporting the control demonstration, the need for improved online monitoring and fault detection of indoor climate, heating and ventilation has been clearly identified. As a part of its future developments, Neogrid will use the results and experience of this project to provide fleet management tools for ventilation systems.

For *Arup & Hvidt* the participation in the project confirmed the importance of operational data in facility management regarding residential buildings. Utilization of data for ensuring that the commissioning of the systems was done properly and at the same time monitoring the systems over their lifetime represents the added clear value. Arup & Hvidt is currently preparing several large renovation projects and the current experiences will be directly transformed into their design as well as tender specifications. Arup & Hvidt realizes that there is a way to go, before the results of the current project can be transformed into robust practical solutions. Mainly, there is a need for a reliable supplier of the technological solutions demonstrated in the project. This is a challenge, as the project partners cannot deliver these solutions directly.

There is a need for new partnerships and collaboration, but the results from the present project show a clear direction to ensure high quality ventilation systems for occupants in apartment buildings.

Insufficient demonstration period caused by delays and other challenges in the project does not allow stating the exact energy savings related to the application of the systems, achievable while maintaining excellent indoor environmental quality. However, the results clearly demonstrate that the system is working with substantially lower airflows, which certainly brings an energy saving potential. Moreover, the results regarding commissioning show that the system enables to detect faults in both installation and operation of the systems. This represents a clear contribution to energy saving policies, as it is possible to monitor whether the ventilation systems operate as intended. Ability to identify unbalanced airflows for particular air handing units represents an important tool for minimizing so called “performance gap” – a difference between designed and real performance.

8. Project conclusion and perspective

- Two ventilation systems were developed and demonstrated within the project.
- Air distribution box that enables precise control of airflow to individual rooms equipped with cloud-based control algorithm was integrated into the decentralized ventilation system in four apartments in Ryesgade 25, Copenhagen. The control algorithm considers both thermal environment and indoor air quality in all rooms of each apartment. The Cloud control algorithm was tested using dynamic computer simulations. Data from indoor environmental quality loggers as well as operational data for air handling unit in the apartment are integrated into the cloud controller. As the project was delayed, it was not possible to realize the whole demonstration as planned. However, the results proved the functionality of the technological concepts as well as functionality of Cloud based control. Comparison to standard constant air volume system showed energy saving 35-70% (64% according to simulation models), however due to incomplete demonstration it was not possible to ensure corresponding IAQ levels. The slightly lower savings can be therefore expected after the system is fine-tuned.
- Room ventilation units BREATHE 55 were connected to the Cloud for continuous performance monitoring. The solution was demonstrated in three apartments in Birkerød. The Cloud based connection enabled verification of unit’s functionality in several control modes, namely temperature and relative humidity control mode as well as frost protection control mode.
- Simulation studies were conducted to study the impact of different boundary conditions (e.g. wind pressure, apartment position) on the performance of room ventilation units. The results showed that selection of fan type plays a crucial role with respect to sensitivity of the room based ventilation units to the wind pressure on the façade as well as stack effect caused by the position of the apartment in the building. To mitigate the impact of stack effect the project proposed using a humidity-controlled damper in the intake to the natural ventilation shaft to reduce the pressure differences across the building envelope.
- The data from simulations represent a technical basis for the financial model assessing benefits of room-based ventilation. It was however not possible to accomplish the development of the financial model itself.
- Performance of commercially available Metal Oxide Semiconductor (MOS) sensors measuring Volatile Organic Compounds (VOC) under different activities typical for residences (e.g. cleaning, cooking, painting, etc.) were studied in field-laboratory setting. The results showed that there were notable difference is performance of sensors from different producers. The results also showed that the sensors from well-established producers detected pollutants in comparable patterns. They

seem to be applicable for the control of "boost" ventilation dealing with sudden increase of unwelcome pollution.

- The project developed and demonstrated a method for online continuous commissioning. Data from air handling systems in particular apartments were analyzed with respect to temperature efficiency of the heat recovery, air flow balance across the units, heat recovery by-pass control, etc. The demonstration the method was extended from eight demonstration units to all 42 air handling units in the apartment building. The method was able to identify air handling units operating inefficiently because of faulty airflow settings, unbalanced airflows and even wrongly installed sensors.

Perspective

Ebm-papst

Technological solutions demonstrated in the project Ebm-papst's air distribution box technology developed during the project has by now progressed to the stage of second prototype. It's first commercial version is planned for 2022. Therefore, the perspective of the project for Ebm-papst is rather straightforward. Despite the fact that the product will be developed completely in within the company and not in collaboration with external partners, Ebm-papst progresses towards introduction of their technology to the market.

Arup & Hvidt

Arup & Hvidt administers old multi-story residential buildings. They realize that there is a need for solutions including the establishment of optimized solutions with regards to demand and requests, operation, maintenance and continuous commissioning of systems in these buildings. Arup & Hvidt have observed that today the solutions on the market are not given the user satisfaction as needed. Moreover, the established players in the today's market do still find this segment of clients too small. This leads to lack of solutions and creates an opportunity. For Arup & Hvidt, the important 'finding' in the project is that the implemented continuous commissioning method actually identified errors in their building. This clearly demonstrates an added value. However, a question remains whether the newly developed method forms the basis for a commercially applicable solution. If it should be applicable on Arup & Hvidt's building portfolio, there must be a possibility "to buy it" and "to operate it". The present project is unfortunately not able to answer these questions. Arup & Hvidt currently plans several large projects where ventilation solutions must be found. The online connected systems have clearly the greatest potential regarding facility management, troubleshooting and continued commissioning.

Sustain Solutions

The initial ambition was a close collaboration with IC-Meter due to the strength of interacting with indoor climate data in the cloud. The original project description included also plans about a cheaper 'junior' unit indoor environmental quality measurement units integrated with room based ventilation. As the project developed, the original business milestones for Sustain Solutions could not be met. Therefore, the focus was moved to demonstration and continuous monitoring of the functionality of room-based units. Customers demand an external control, preferably by mobile phone apps. The economy for investing in new solutions is affected by smaller product sales than expected, but new solutions may emerge in the long term. There are two hardware solutions that must be facilitated - private user segment where wireless solutions are preferred and segment of large installation companies, where the tested solution utilizing Modbus connection can be an option. The BREATHE 55 unit is prepared for both. In initial dialogues with housing associations, there was actually interest in data, if it is accessible in manageable way. The current project has demonstrated the potential; however, it is still far from a commercial solution. In the course of the project, Sustain Solutions decided to sell the product – BREATHE 55 to another commercial partner.

Neogrid Technologies

Despite the fact that Neogrid did not have influence of the initial design of the technical solutions (as it joined the project later), the company is deeply involved in other projects dealing with data-driven building HVAC monitoring and control. Data analysis, visualization and intelligent control is one of Neogrid's key added values to its customers. As the company is currently working mostly with heating related projects, the current project has given valuable insights into the field of ventilation control and monitoring. As a part of its future developments, Neogrid will use the results and experience of this project to provide fleet management tools for ventilation systems, as well as improve its existing control and monitoring tools for ventilation.

9. Appendices

9.1 The impact of wind pressure and stack effect on the performance of room ventilation units with heat recovery

Energy & Buildings 234 (2021) 110689

Contents lists available at ScienceDirect

ELSEVIER

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

The impact of wind pressure and stack effect on the performance of room ventilation units with heat recovery

Check for updates

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ARTICLE INFO

Article history:
Received 29 July 2020
Revised 4 December 2020
Accepted 21 December 2020
Available online 24 December 2020

Keywords:
Decentralized ventilation
Room ventilation units
Façade ventilation
Heat recovery
Rotary heat exchanger
Stack effect
Centrifugal fans
Axial fans
Humidity-controlled damper

ABSTRACT

Room ventilation units (RVUs) with heat recovery represent an alternative ventilation solution for renovated residential buildings, allowing simple installation through the façade. However, wind pressure on the façade can have a substantial impact on fan performance and thus affect the airflows through the RVU. Airflow imbalances between supply and exhaust negatively affect total heat recovery and supply air temperatures. Moreover, RVUs installed in apartments on the ground floor of multi-story buildings with a natural ventilation shaft are highly affected by negative pressures due to stack effect during winter periods. The issues that characterize these units were examined in this study in relation to the fan type and fan operation, aiming to establish why the performance is varying for different units. The study simulated the performance of RVUs in a typical Danish test apartment under various wind pressure conditions. To investigate the combined impacts of wind and stack effect, the simulations assumed the test apartment being located on the ground floor of a 4-storey building with an 11-meter natural ventilation shaft. The authors performed dynamic annual simulations with different fan characteristic curves and fan operating points for centrifugal and axial fans. Simulations tested the additional impact of adding a humidity-controlled damper in the intake of the natural ventilation shaft to reduce pressure differences across the building envelope due to stack effect. Results showed that centrifugal fans were less sensitive to pressure differences than axial fans due to their steeper fan curves and generally higher operating pressures. When taking into account wind pressure and disregarding stack effect, the sensible heat recovery decreased by up to 8% in RVUs with centrifugal fans and up to 22% in RVUs with axial fans at the same airflow settings. After including stack effect, the decrease in sensible heat recovery was instead up to 20% for RVUs with centrifugal fans and up to 52% for RVUs with axial fans. The inclusion of a humidity-controlled damper reduced the pressure differences due to stack effect and halved the negative impact on sensible heat recovery on average. As a result, the RVUs were able to provide considerably higher supply air temperatures. The study showed that a humidity-controlled damper could reduce the negative impact of stack effect on the performance of an RVU.

The full article is available at https://doi.org/10.1016/j.enbuild.2020.110689

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

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Published in:
I O P Conference Series: Materials Science and Engineering

Link to article, DOI:
10.1088/1757-899X/609/3/032041

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

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

To cite this article: K M Smith and J Kolarik 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 032041

IOP Conf. Series: Materials Science and Engineering **609** (2019) 032041 doi:10.1088/1757-899X/609/3/032041

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.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 032041 doi:10.1088/1757-899X/609/3/032041

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.

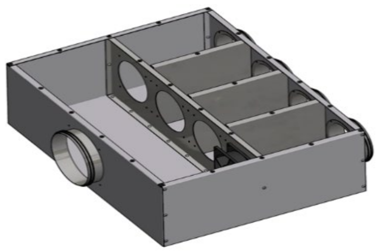

Figure 1. Drawing of the distribution manifold.

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

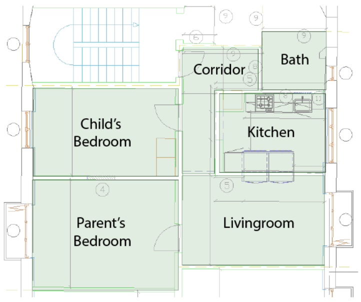

Figure 2. Floorplan of the demonstration site.

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 kg_{H2O}/kg_{AIR} and 0.012 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, ρ is the air density and Δp 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.

$$\dot{m}_{leak} = C_d A_o \sqrt{2\rho\Delta p} \quad (1)$$

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

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, $V_{nominal}$, 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_{actual}.

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

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.

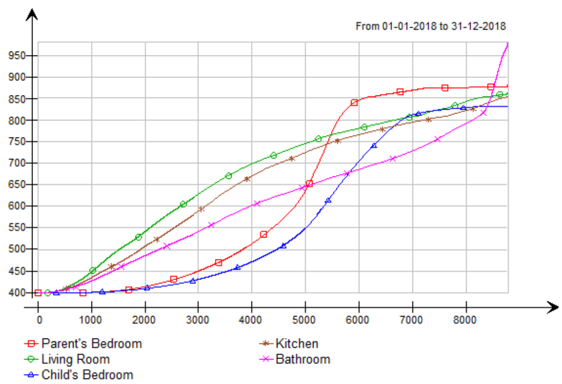

Figure 3. Duration curve of CO_2 concentrations with room-based demand-control.

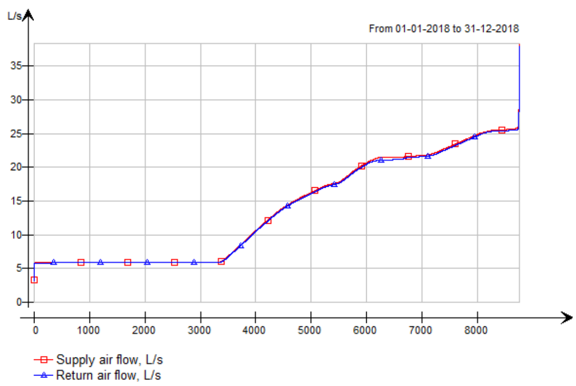

Figure 4. Duration curve of supply and exhaust airflows with room-based demand-control.

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.

References

[1] Danish Energy Agency 2012 *Energistatistik*
[2] Morelli M, Rønby L, Mikkelsen SE, Minzari MG, Kildemoes T and Tommerup HM 2012 *Energ. Buildings* **54** 395
[3] Danish Energy Agency 2014 *Denmark's National Energy Efficiency Action Plan*
[4] Ridley I, Fox J, Oreszczyn T and Hong S 2003 *Int. J. Vent.* **3** 209
[5] Villi G, Peretti C, Graci S and De Carli M 2012 *J. Build. Perform. Simu.* **2** 1
[6] Wetter, M 2011. In Hensen JLM and Lamberts R *Building Performance Simulation for Design and Operation*.
[7] Gunner A, Hultmark G, Vorre A, Afshari A and Bergsøe NC 2014 *Energ. Buildings* **84** 360
[8] International Organisation for Standardisation 2007 *ISO 15251*
[9] Smith KM and Svendsen S 2016 *Energ. Buildings* **116** 349
[10] International Organisation for Standardisation 2006 *ISO 7730*
[11] Hite SC and Bray JL 1948 *Engineering Experiment Station, Research Series No.* 106
[12] Yik FWH, Sat PSK and Niu JL 2004 *Indoor Built Environ.* **13** 115
[13] Shah RK and Sekulic DP 2003 *Fundamentals of heat exchanger design*.
[14] American Society of Heating, Refrigerating and Air-Conditioning Engineers 2016 *Standard 90.1*

9.3 Metal Oxide Semiconductor sensors to measure Volatile Organic Compounds for ventilation control

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Metal Oxide Semiconductor sensors to measure Volatile Organic Compounds for ventilation control

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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Kolarik, J., Lyng, N. L., & Laverge, J. (2018). *Metal Oxide Semiconductor sensors to measure Volatile Organic Compounds for ventilation control*.

Metal Oxide Semiconductor sensors to measure Volatile Organic Compounds for ventilation control

Report from the AIVC Webinar: "*Using Metal Oxide Semiconductor (MOS) sensors to measure Volatile Organic Compounds (VOC) for ventilation control*", held on September 4, 2018

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1. Introduction

The application of Metal Oxide Semiconductor (MOS) sensors measuring Volatile Organic Compounds (VOC) gains increasing attention in the ventilation community because of their low price and claimed ability to supplement or even substitute CO_2 sensors for demand controlled ventilation (DCV). Even though there are many "Indoor Environmental Quality" meters available on the market, in which these sensors are used, the amount of scientific studies focused on their reliability and applicability is still limited. Moreover, it seems that, although several ventilation producers offer VOC based control, these solutions are not implemented at large scale in the market.

During the AIVC webinar held on 4 September 2018, participants of IEA EBC Annex 68 presented research results, experiences and thoughts related to MOS VOC sensors. The aim of the webinar was to intensify discussion on the topic of low-cost sensors in the ventilation community.

The focus of the webinar was to introduce research projects focused on providing insight in functionality, behaviour and usability of MOS VOC sensors for ventilation control. This paper summarizes the presentations from the webinar. Section 3 discusses "Can MOS VOC sensors be used for ventilation control?", presented by Nadja L. Lyng, section 4 "MOS VOC sensors' properties and suitability for DCV control" by Jakub Kolarik and section 5 "VOC versus CO_2 controlled DCV: A case study" by Jelle Laverge. The main take-aways and perspectives for MOS VOC sensors in ventilation systems are summarised in the conclusion section.

2. Background

MOS sensors measuring VOC seem to be an obvious step towards broadly available Demand Controlled Ventilation (DCV) [1]. Firstly, MOS VOC sensors offer the possibility to not only account for pollution related to human presence, like currently used CO_2 sensors, but also register diverse odorous events taking place in a space. The fact that these sensors are sensitive to a broad range of chemicals can be advantageous from the point of view of indoor air quality – ventilation is started also in the cases of emission of pollutants that are undetectable by standard CO_2 sensor. Secondly, MOS technology allows producing sensor units that are cheaper and less power demanding than current Non-dispersive infrared (NIDR) CO_2 sensors. This indicates that DCV ventilation could be applied also in projects, where high price of sensors as well as installation costs disqualify traditional DCV.

All above mentioned arguments speak for MOS VOC sensor technology in comparison to the currently used CO_2 based one. However, recent research shows that simple replacement of CO_2 sensors with VOC sensors is not enough to achieve the desired effect [2, 3, 4]. A ventilation control strategy needs to be tuned specifically for use of VOC sensors so that their potential can be utilized. In addition, recent studies on use of MOS VOC sensors for ventilation control [3, 4, 5, 6] focused mostly on potential energy savings, but the fact whether their application influences indoor air quality with respect to concentration of particular pollutants was not investigated. The broad sensitivity of the MOS sensors, mentioned earlier as an advantage, turns out to be a disadvantage when issues like measurement accuracy and calibration are taken into account. Broad sensitivity is also a disadvantage if the sensors react to short-term "non-problematic" VOCs emissions like ethanol, perfume or limonene from oranges.

If MOS VOC sensors should be widely applied in practice, as not only air quality indicators in cheap "home IEQ data loggers", but for control of ventilation, more rich and detailed information about their performance is needed.

3. Can MOS VOC sensors be used for ventilation control?

As mentioned in the introduction, the MOS VOC sensors seem to present an inexpensive method to measure real time changes in concentration of the total amount for VOCs (this aggregated measure is usually called Total Volatile Organic Compounds - TVOC). The research project conducted in collaboration between Technical University of Denmark, Danish Technological Institute and Aarhus University had the objective to study the response of commercially available MOS VOC sensors to pollutants emitted during activities typical for residences.

The experiments were conducted at a full-scale test room. Investigated activities included painting, cleaning, candle burning, emission of human bioeffluents, changes of relative air humidity, emission from linoleum flooring and dosing of ethanol into the test room.

Five commercially available sensors were tested (abbreviated as A, B, C, D and E). Four of them were equipped with an embedded algorithm for so-called auto-calibration. The functionality of the algorithms was unknown to the researches, however a general functionality of auto-calibration is to utilize the lowest measured concentration over a longer period as a "clean air" baseline. A very precise analytical instrument - the Reaction-Time of Flight-Mass Spectrometer (PTR-ToF-MS) was used as a reference measurement. This measurement was used to determine total concentration of VOC in the test room, so called $TVOC_{PTR\text{-}TOF\text{-}MS}$.

All pollution activities resulted in changes in the air quality that were detected by the MOS VOC sensors as well as the PTR-ToF-MS. Figure 1 shows an example of results for emission of human bioeffluents and changes in relative air humidity. The grey areas indicate the duration of the pollution activity. The top three graphs show the signal of the MOS VOC sensors and the bottom graph shows the $TVOC_{PTR\text{-}TOF\text{-}MS}$ concentration. The top graph shows sensors A and B (two specimen of each type). The yellow and green coloured data shows sensor A. The measuring signal is incomplete for sensor B1 because the sensor was by mistake set to the low measuring range with upper border of 600 ppm. The second top graph shows sensor type C, of which five specimens were tested. The second bottom graph show result from sensor type D of which two specimens were tested.

During emission of human bioeffluents, data for all MOS VOC sensors clearly show similar concentration patterns, but there are clear differences in absolute concentrations. This difference was observed among the sensor types, but also among specimen belonging to each sensor type. The data obtained during tests with alternated relative humidity levels show that relative humidity levels in the test room clearly had an influence on measured signals.

The experiments showed that tested MOS VOC sensors were able to detect changes in VOC concentration during different pollution activities, but the measured signals differed in absolute values as well as in the amplitude of signal change. As documentation provided by manufacturers and suppliers was very limited regarding calibration and accuracy of the sensors, further testing would be necessary to characterize performance of particular sensors. The results indicate that in order to use MOS VOC sensors for controlling ventilation, there is a need for further post processing of the sensor signals. And since the effect of temperature or long time use was not tested during the present test, it should be tested in future if or how temperature affect the sensor signals and the reliability of the sensors being in use over longer periods. To answer the question "Can TVOC sensors be used for ventilation control?" in short it is important to highlight that MOS VOC sensors cannot directly replace CO_2 sensors in existing ventilation systems. This conclusion is supported by other research studies, for example Moreno-Rangel et al. [7]. Their application needs to be accompanied with additional signal processing, which needs to be specifically tuned for a particular type of sensor and application.

4. MOS VOC sensors' properties and suitability for DCV control

The second presentation at the webinar aimed to illustrate the nature of the MOS VOC signal and suggest how to determine sensor properties like sensitivity or linearity. The presented analysis was based on the data collected during the experiments described in Section 3P a g e | **3** of this paper. Data from the air polluting activity "Cleaning" will be used as an example.

Due to the operating principle of the MOS technology, the MOS VOC sensors provide a relative signal – a relative change of VOC concentration. Because of that, it is difficult to compare absolute values of concentrations measured by several sensors, even from the same producer. To deal with this problem, sensor signal data can be normalized, for example using mean concentration calculated using data for 3 hours before initiation of the polluting activity, or so called min-max normalization known from the field of data mining.

Figure 2 shows the difference between absolute and normalized concentrations for the cleaning activity. The figure shows data for two specimens of two of the tested MOS VOC sensor types. The sensors produce signals of a similar pattern, but it can be clearly seen that absolute concentrations (Figure 2Figure 1- top) differ even between sensors of the same type (producer). When sensor signals were normalized by the background concentration obtained in the empty test room before the cleaning activity (Figure 2-bottom), the sensors produced signals that were comparable not only with respect to the pattern, but also the magnitude of the concentration change.

Several producers try to address the problem of the relative nature of the measurements using so called auto-calibration algorithms embedded in the sensors' print boards. Auto-calibration algorithms are obviously proprietary, and producers do not disclose their exact functionality on the product data sheets. In general, the auto-calibration is supposed to ensure a "measurement baseline" determined using lowest measured concentration over certain (sufficiently long) period. Such approach assumes firstly, that sensor is activated in "clean air" conditions, secondly, that periods with "clean air" are ensured from time to time during the operational lifetime. Violation of the latter assumptions may lead to establishing of a wrong baseline, which does not represent "clean air". Consequently, harmful VOCs, such as formaldehyde, which are continuously emitted from some building materials, will not be accounted for. As the sensor itself cannot determine whether baseline conditions truly represent "clean air", this would need to be ensured by the operator of the ventilation system.

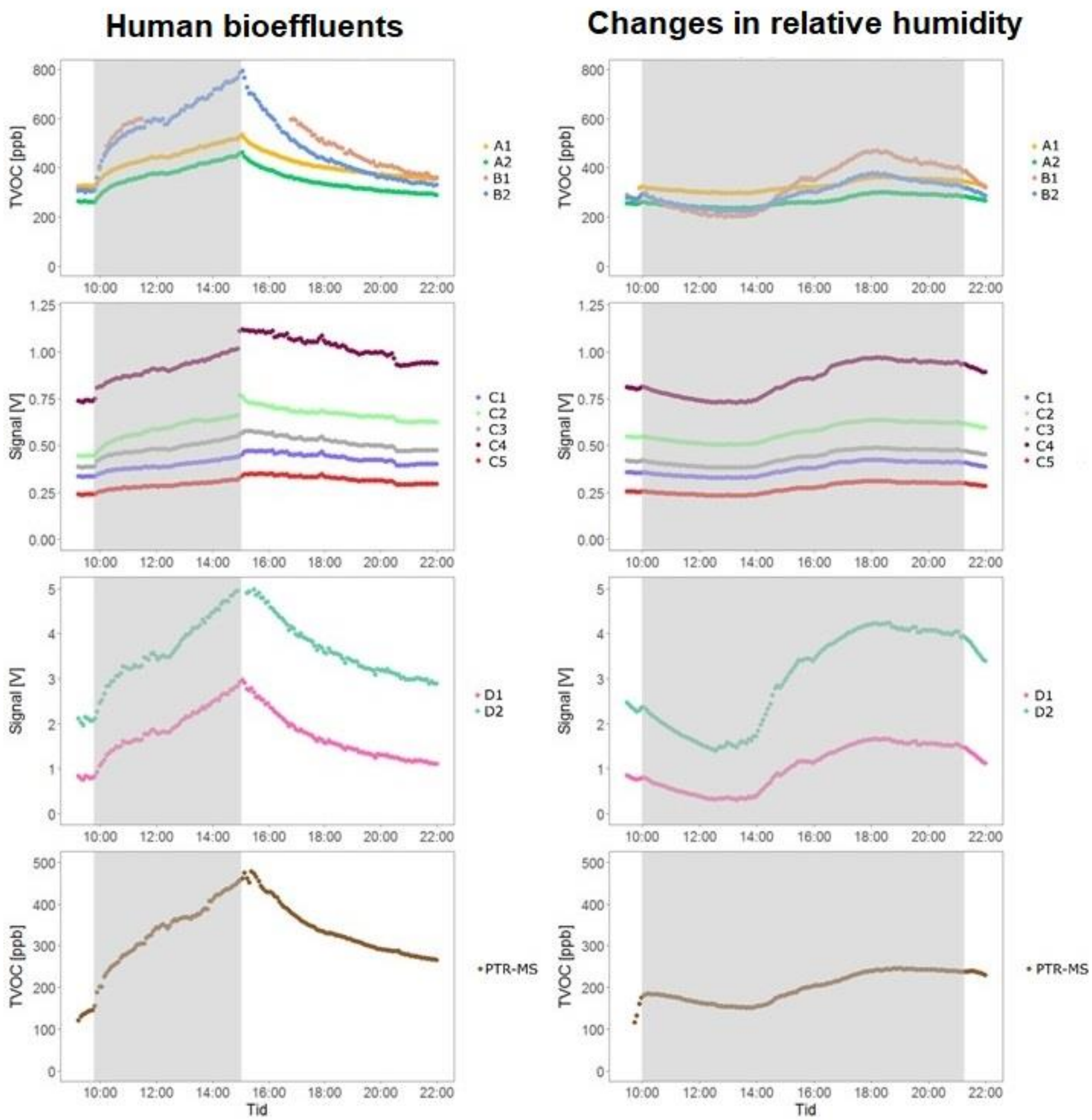

Figure 1: VOC-sensor response to activities with people as pollution source and changes of the relative humidity; the graph in the bottom is the sum of all measured compounds by PTR-ToF-MS and can be used as a reference

Knowledge of the sensor properties can help with identification of a suitable sensor for a practical application. Figure 3 shows a comparison of sensitivity for MOS VOC sensors A and B when exposed to pollution activities cleaning, emission of bioeffluents and emission from linoleum. The sensitivity represents a magnitude of change of MOS VOC signal related to a change in a reference signal. It was determined using work by Fahlen et al. [9]. It can be seen from the figure that the sensitivity differed among the pollution activities. It was highest during the cleaning activity. Moreover, sensor B was in general more sensitive than sensor A. The differences in sensor sensitivity under different pollution activities can most probably be explained by the fact that different compounds were emitted during the activities and therefore characterize the emissions. MOS VOC sensors' active layers reacted differently to those chemicals. It is not a goal of the present paper to analyse the undergoing mechanisms, but the results seem to support practical observations that MOS VOC sensors react strongly to pollution generated by detergents, paints or human presence, while reaction to background pollution from building materials is rather moderate.

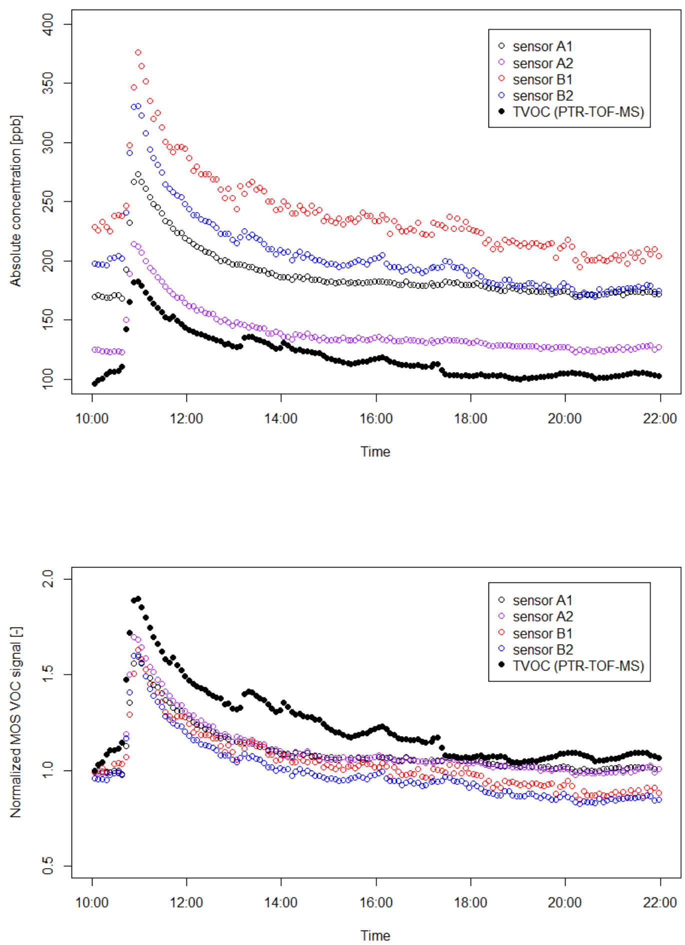

Figure 2: (top) Comparison of TVOC (PTR-TOF-MS) signal and absolute signal from two types of MOS VOC sensors (A and B) during cleaning activity, (bottom) normalized signal from two types of MOS VOC sensors; data from two specimens per MOS VOC sensor type are shown

In practice, the sensitivity of the sensor can help in the selection for an appropriate sensor with respect to its application. For example, if the sensor is supposed to account both for human occupancy and short term pollution events like cleaning, sensor B seems to be more suitable, because its sensitivity to human generated pollution is comparable to the sensitivity to pollution from cleaning.

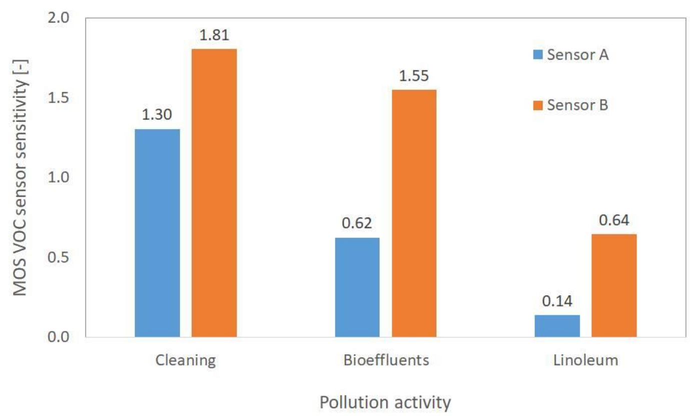

Figure 3: Sensitivity of MOS VOC sensors A and B during cleaning, emission of bioeffluents and emission from linoleum

However, these data do not give any advice regarding ventilation control. More precisely, due to the need for normalisation, it is very hard to establish limit concentration values corresponding to minimum and maximum airflow provided by ventilation system. The need for auto-calibration makes these sensors mainly useful for event detection. An option to determine limit concentrations for practical event based controls is using exposure to a pollution activity, during which the ventilation system must provide maximum available airflow. One example could be painting, but in office environment different cleaning activities would represent more suitable events.

5. VOC versus CO_2 controlled DCV: A case study

As discussed above, DCV possesses the ability to control ventilation rates by using concentration levels of pollutants in occupied space. Most commercially available systems use CO_2 as an IAQ control signal based on established correlations between the perceived air quality and CO_2 concentration [10]. There are, however, important drawbacks with CO_2 sensors from an engineering point of view: the most common types, based on Non-dispersive Infrared (NDIR) technology, are still rather expensive and, energy intensive due to the necessity to heat them for good operation, . MOS VOC sensors are a much more energy efficient and cost effective alternative, but, as clearly demonstrated above, their signal value is non-compound specific and they are not able to measure real CO_2. The appear to be mostly suited to detect additional ventilation events.

In the case study introduced in the third presentation of the webinar, the effect of using the auto-calibrated MOS VOC sensor signals in in the field was studied by controlling real DCV systems by either the real CO_2 concentration or a CO_2 equivalent VOC concentration.

For the test, 32 newly built or renovated dwellings in a social housing complex near the Kortrijk city center in Belgium, with recently installed mechanical exhaust ventilation systems with demand controlled dampers in each of the individual exhaust ducts were selected. CO_2 and MOS VOC sensors were installed side by side on the extraction dampers of the kitchens and (in some dwellings) bedrooms. These were designed to be controlled by either of these sensors in a flexible demand controlled ventilation approach.

The MOS VOC sensors provided sensors that can output so-called CO_2 equivalent concentration [7, 10]. Thus, the amount of emitted VOC was correlated to human emission of CO_2. The system started with CO_2 based control, but switched to MOS VOC based control after two weeks of operation.

The sensor signals, as well as the damper positions were logged with the internal of 90 s. In the end, 12 weeks of data was gathered from 29 of the selected dwellings (dampers for 28 kitchens and 18 bedrooms).

Figure 4 shows the CO_2 and CO_2-equivalent MOS VOC concentrations over the course of 2 weeks of measuring. In the first week, the flow rate was controlled by adjusting the damper position based on the CO_2 concentration, with a set point of 900 ppm. As can be seen in the figure, the set point is barely reached and the damper remains closed (bottom grey line in the graph) except one time. During the second week, the flow rate was controlled by VOC concentration. The concentration was more variable and affected by higher peaks. The damper was opened much more frequently when occupants were present due to high concentrations, but the system was not able to keep the CO_2-equivalent MOS VOC concentration below or around the set point.

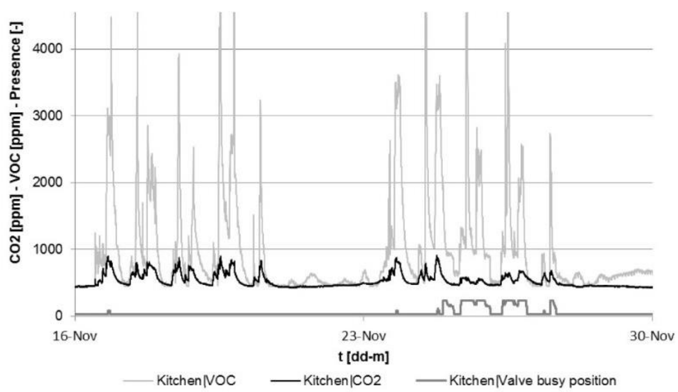

Figure 4: CO2, MOS VOC and damper position over 2 weeks

When the CO_2 and VOC concentrations are compared (note that they were measured at the same point in the damper), the general pattern is rather similar, but the MOS VOC concentration has, as was mentioned above, a much higher variability, and is affected by the higher VOC peaks. This is consistent with the claim of the manufacturers of the sensor that it is calibrated to represent metabolic CO_2, but also reacts to other sources. As was shown in the experiments presented above, the sensor may be much more sensitive to these events, explaining the peaks observed.

The mentioned divergence between CO_2 and MOS VOC concentrations is clearly visible through the differences in daily concentration patterns. Figure 5 shows a plot with all concentrations measured during a time scale of 24 hours. The largest differences among these patterns can be characterized as:

(1) generally higher MOS VOC concentrations compared to CO_2;
(2) strong variability of the MOS VOC concentration, with high peaks during day time (more ‘events’);
(3) steep build-ups and decays of the MOS VOC concentration

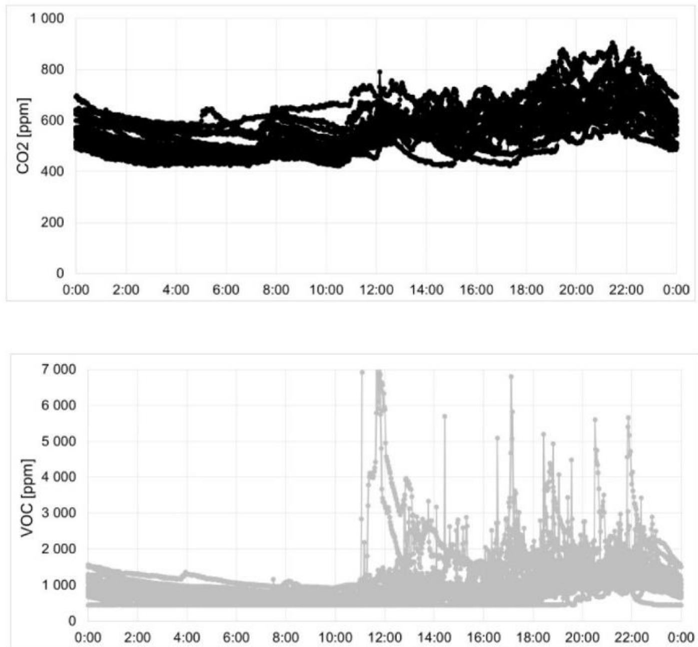

Figure 5: CO_2 (top) and VOC (CO_2 equivalent) (bottom) concentration day profiles in kitchens during the measurement campaigns

Based on the results from this case study, it is concluded that, when considering MOS VOC sensor based concentration as a control signal for DCV, HVAC designers need to take into account that the total ventilation rate will likely be significantly higher compared to CO_2 based DCV control, with more frequent and steeper changes in flow rates. This will likely result in better IAQ since more pollution events can be detected. However, the design flow rate for the system can still be a limiting factor. In addition, as the MOS VOC sensors are non-selective, their use in the control can potentially trigger unnecessary ventilation, especially if the signal is used for both bioeffluents and other events. The consequences for energy performance, and especially user acceptability of such a system, e.g. due to higher perceived noise levels, need to be studied further.

6. Conclusions

MOS VOC sensors are inexpensive, consuming low power and very often internet connected. They can be deployed in large amounts. Their data can be easily accessible using different mobile platforms. However, their ability to indicate indoor air quality and their applicability for control of ventilation systems is associated with many pitfalls and challenges, which are often unclearly articulated.

The experiments demonstrate that suitability of a specific sensor for a specific purpose should be carefully evaluated in practice. In general, MOS VOC sensors seem to be capable of indicating increased emissions of VOC in indoor spaces. However, due to the relative nature of their signal, their integration into ventilation control remains challenging.

The results show that MOS sensors are useful to detect VOC intensive events such as high occupancy, cleaning, painting, or toilet use. In practice, it is important to ensure sensor start-up in clean air and provide regular thorough ventilation to ensure that the sensor’s baseline represents clean air compared to the events that it is used to target. MOS VOC sensors can be successfully used to trigger the ventilation in such events, but are not reliable enough for continuous monitoring for typically nearly constant pollution sources such as emissions from building materials.

7. Acknowledgments

Jakub Kolarik and Nadja Lynge Lyng would like to acknowledge Danish Landowners Investment Fund and The energy technological development and demonstration program (EUDP) for support of their research.

Jelle Laverge would like to thank the occupants of the dwellings and the housing association 'De goedkopewoning' for their support during the measurement campaign.

8. References

[1] Herberger, S., Ulmer, H. (2012) Indoor Air Quality Monitoring Improving Air Quality Perception. Clean-Soil Air Water, 40 (6), 578-585.

[2] Kolarik, J. (2014) CO_2 Sensor versus Volatile Organic Compounds (VOC) sensor – analysis of field measurements and implications for Demand Controlled Ventilation. In proceedings of Indoor Air 2014, Hong-Kong, China.

[3] Merzkirch, A., Maas, S., Scholzen, F., Waldmann, D. (2015) A semi-centralized, valveless and demand controlled ventilation system in comparison to other concepts in field tests. Building and Environment 93, 21-26.

[4] Abdul-Hamid, A., El-Zoubi, S., Omid, S. (2014) Evaluation of set points for moisture supply and volatile organic compounds as controlling parameters for demand controlled ventilation in multifamily houses. In proceedings of Indoor Air 2014, Hong-Kong, China.

[5] Abdul Hamid A., Wallentén, P., Johansson, D. (2015) Moisture supply Set Point for avoidance of moisture damage in Swedish multifamily houses). In proceedings of 6th International Building Physics Conference, IBPC 2015, Torino, Italy.

[6] Pollet, I., Bruyneel, G., Vens, A (2015) Comfort in naturally ventilated offices: in situ measurements. In proceedings Healthy Buildings Europe 2015, Eindhoven, The Netherlands.

[7] Moreno-Rangel, A., Sharpe, T. , Musau, F. and McGill, G. (2018) Field evaluation of a low-cost indoor air quality monitor to quantify exposure to pollutants in residential environments, J. Sensors Sens. Syst., vol. 7, no. 1, pp. 373–388.

[8] Fahlen, P., Andersson, H., Ruud, S. (1992) Demand Control Ventilating Systems - Sensor Tests, SP Report 1992:13, Swedish National Testing and Research Institute, ISBN 91-7848-331-331-x, available from: https://iea-ebc.org/projects/project?AnnexID=18 (visited September 2019).

[9] Herberger, S., Herold, M., Ulmer, H., Burdack-Freitag, A., Mayer, F. (2010) Detection of human effluents by a MOS gas sensor in correlation to VOC quantification by GC/MS. Building and Environment, 45, 2430-2439.

[10] van Holsteijn, R. C. A., & Li, W. L. (2014). Monitoring the energy & IAQ performance of ventilation systems in Dutch residential dwellings. In proceedings of 35th AIVC Conference "Ventilation and airtightness in transforming the building stock to high performance" (pp. 467-477), Poznan, Poland.