Offerings and challenges of demand response ventilation under covid-19 scenarios

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Abstract

Owning to the outbreak of COVID-19, individuals have to spend more time indoor. It is therefore essential to prepare for a long-term healthy indoor working environment in the transition of post COVID-19 pandemic. However, there is no relevant research so far in investigating such crisis impacts around indoor environmental quality and economic-health issues while home offices are expected becoming common practice soon. Therefore, a case of single-family house in Sweden is specially investigated using IDA ICE. By comparing four predominant ventilation approaches, three operational schedules are proposed, covering different confinement for occupants. Main results show that the demand response ventilation (DRV) generally should sacrifice in remarkable performance in energy saving, and emission reduction to better confront with more challenges in indoor air quality, occupied thermal dissatisfaction fraction and air stagnation under the challenge of COVID-19 pandemic scenario. Altered ventilation strategy should be customized from increased outdoor air supply, various demand-control signal, displacement method towards a heathier home-working environment.

Key Innovations

- This study compares four mechanical ventilation approaches, i.e. the fixed exhaust, the CAV (Constant Air Volume) occupancy controlled, and the DRV (including exhaust only and supply/return modes);
- It investigates the DAV strategy for a single family house under the scenario of covid-19 pandemic by considering three different operation schedules (“normal as usual”/ ‘soft’ locked down/‘strict’ locked down modes);
- The research covers the full key performance indicators (KPIs) to re-evaluate the effectiveness of DRV system, such as indoor air quality (IAQ), energy, thermal satisfaction and air stagnation.

Practical Implications

The altered DRV strategy in accordance to each refinement level should supplement in conventional ventilation methods to address prevention, preparedness, resilience and recovery in relation to COVID-19 and other respiratory infections. The subtle improvements can be suggested to have supervisory control refinement in ventilation system, effective air freshness measures, and other impacting reasons, which would be external exposure of the demand responded room, accuracy and dead band inside demand control algorithms, and indoor temperature variation caused by internal gains.

Introduction and motivation

The indoor environment heavily influences the health, productivity, and comfort of its occupants. The systems used to maintain the environment also significantly affect the overall energy consumption of the building. An efficient and well-operated HVAC system is one of the most important components of building design. Especially in the past a few months, the COVID-19 crisis has significantly affected all aspects of our life, such as human health and well-being, economy, social activities, energy demand, and built environment. Sweden is trying resilient confinement measures to reduce the impact of this pandemic. One of the measures is to encourage people working from home to keep social distance (Public Health Agency of Sweden, 2020).According to the Swedish Internet Foundation (2020), more than two thirds of Swedes already work online from home for certain time, with around a third doing this on a daily or weekly basis. Depending on the Statista (2020) from 2009 to 2018, about 48% companies allowed employees working from home in average. The existing social and company policies in Sweden champion flexible and remote working culture as part of a balanced and gender-equal lifestyle. Now with the impact of crisis like COVID-19, it is predictable that more and more people will work from home with longer time. During the normal periods, individuals spend more than 85% of their total time in indoor environments for home stay and work. In the special period of COVID-19 or similar crisis, this percentage is even higher up to 100% for a fully lock-down scenario. It is therefore important and necessary to prepare for a long-term healthy home-working environment in the transition of post COVID-19, which should be not only functional, but also comfortable, ergonomic and supportive for both physical and mental health.

Although a few studies have started to investigate the home-working mode, most of them only concentrate on potentials of energy demand reduction, energy demand shifting and ‘smart’ controls at homes (Hampton, 2017) or in land use (Fu et al., 2012), transportation infrastructure (Cerqueira et al., 2020) through behaviour change. The other researchers connect occupation and gender with health issue in the home-working condition. For instance,

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Kollmann T et al. (2019) focused on work-home interference of entrepreneurs and their sleep (insomnia). They found that both novice and experienced entrepreneurs suffer from insomnia when encountering entrepreneurial stressors by working from home. Particularly, Kramer A. and Kramer K. (2020) recently accessed the potential impact of the Covid-19 pandemic on occupational-related social concerns. They concluded that working from home may change occupational perspectives, which may increase and broaden income, gender, racial, and ethnic inequality. Brewis J (2019) also wrote an editorial letter to encourage more research about women in the mode of working from home due to the COVID-19, where she highlighted that working from home may have both positive and negative health and socioeconomic impacts. To the best knowledge, there is no research so far in investigating the impact of crisis, as COVID-19 pandemic, on indoor environmental quality (IEQ) in residential buildings, where homes are becoming working place on a more regular basis.

The IEQ of a building is the most important factor that affects occupants' health and well-being from a diverse point of view (Spengler J. & Sexton K., 1983; Andargie et al., 2019). Vehviläinen T. et al, (2016) indicated that high indoor CO_2 concentrations increases the sleepiness during cognitive work. Wang J. et al., (2020) pointed out that dampness and mold at home and at work can lead to insomnia symptoms, snoring and excessive daytime sleepiness. Budd and Warhaft (1996) discovered that blood pressure increased significantly with uncomfortably low temperatures. Particularly, in case of the COVID-19 pandemic outbreak, more occupants have to stay or work at home for longer time. Such new occupancy condition causes issue in air stagnation that may concentrate airborne viruses or dust indoor, which will decrease the IAQ and influence occupants' health. Moreover, during the COVID-19 or similar crisis, flexible environment at home is generally beneficial, but it is also challenging owing to the presence of partners and/or children, lack of communications with colleagues, limited food, less working percentage or opportunity, and limited resources for health assessment etc. All of these will influence on peoples' psychological and physiological response, as well immune system (International WELL Building Institute, 2020), whose consequence stays unclear in Swedish home context. Thus, it is critical to start an investigation about the impact and the effective means to improve IEQ in response to COVID-19 or similar pandemic. This paper begins with the exploration of mechanical ventilation system in a residential building. The research results are useful to propose adaptive strategies for healthier home indoor environment in the future.

Case description and research methodology

The studied case building, shown in *Figure 1,* is a single-family demonstrative house located in the Dalarna region, Sweden. The project was financed by the insurance company Dalarnas Försäkringsbolag. It is a two-storey wooden construction on a concrete slab foundation. Heating is from a ground-source heat pump with underfloor distribution, while there was no space cooling until this article composed. The internal footprint is 88 m^2 and the total floor area 150 m^2. Due to the living room being double height, the internal volume is about 500 m^3.

The whole research methodology is briefed as below:

- Establishing the basic building geometry and material properties based on the information from *Table 1*;
- Refining the building model with the help of additional building plans and specifications from the designer Fiskarhedenvillan, Sweden;
- Inputting default values in IDA ICE for all other common materials in throughout the house;
- Assuming all user relevant inputs databased on recommendations from the Sveby guidebook (2012);
- Once the baseline model developed, four predominant mechanical ventilation approaches are set via central air handling unit, e.g. the fixed rate mechanical extraction ventilation, the occupancy-dependent ventilation and the DRV (including exhaust only and supply/return modes). In addition, three lock down occupancy scenarios are assumed to represent three general types of confinement level, as 0% for "normal as usual" mode, 50% as 'soft' locked down mode, and 75% as 'strict' locked down mode. Detailed information are summarized in *Table 2*.

Figure 1 Reality capture of Dalarnas Villa

Table 1 Input data on building, climate conditions and installations in the house

Input	Value	Unit
Location	Falun	
Design outdoor temp. [1]	−19,7	°C
Air Tightness (q50)[2]	0.18	$l/(s \cdot m^2)$
Mean U-value (U_m) [2]	0.269	W/K m^2
$U_m A_{tol}$[2]	120.1	W/K
Time Constant[2]	62	hours
Indoor Temp. [2]	21	°C
Occupants[2]	3.5	Per.
Occupancy[2]	14	h/d/per.
Internal Gains (occupancy) [2]	80	W/per.
Household Electricity[2]	30	kWh/m^2/år
Domestic Hot Water[2]	20	kWh/m^2/år
Conditioned Floor Area (A_{temp}) [2]	150.4	m^2
Building Envelope (A_{om}) [2]	446.5	m^2

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Ground Source Heat Pump [2]	5.3	kW
COP, 0/35°C[2]	4.62	-
COP, 0/45°C[2]	3.44	-
COP, 0/55°C[2]	2.64	-
On-site Generation (PV) [2]	5074	kWh/år
SFP (kW/(m^3/s))	0.8	
Efficiency	0.8	
Pressure rise (Pa)	640	
Given air temp. Rise	Constant with 1 °C	
Energy information	Primary energy factor =1.6 CO_2 emission per kWh = 40g/kWh	

Note:[1] *(SVEBY, 2016);[2] (Petrovic, B.et al., 2019);[3] IDA ICE default assumed; [4](Swedish Standard SS-EN 15251, 2007)*

Table 2 Studied variant types of mechanical ventilation strategies and different occupied schedules

Variants		*Lock Down Level*	*Description*
1Ai	Base Case,	0%	***Fixed exhaust ventilation*** with the baseline rate according to BBR requirement through extraction from all zones.
1Aii		50%	
1Aiii		75%	
1Bi	1B	0%	***Fixed exhaust ventilation*** with baseline rate according to BBR requirement through extraction from wet rooms only (kitchen and bathrooms)
1Bii		50%	
1Biii		75%	
1Ci	1C	0%	***Fixed exhaust ventilation*** at rate of 130% of BBR requirement with extraction from all zones.
1Cii		50%	
1Ciii		75%	
2i	2	0%	***CAV Occupancy controlled ventilation*** **(exhaust only)** with rates of 100% of BBR requirement when occupied, and 30% of BBR requirement as a background rate during unoccupied period
2ii		50%	
2iii		75%	
3Ai	3A	0%	***Demand-controlled ventilation*** **(exhaust only)** with high and low rates (30%/100% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide (Borlänge Energi, 2020) in dry rooms and relative humidity in wet rooms (Kim SW et al., 2007; Dietzin L. et al., 2020)
3Aii		50%	
3Aiii		75%	
3Bi	3B	0%	***Demand-controlled ventilation*** **(exhaust only)** with high and low rates (30%/130% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide[1] in dry rooms and relative humidity in wet rooms[2].
3Bii		50%	
3Biii		75%	
4Ai	4A	0%	***Demand-controlled ventilation (supply and return)*** and heat recovery with high and low rates (30%/100% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide[1] in dry rooms and relative humidity in wet rooms[2]. Zones set to individual sensors.
4Aii		50%	
4Aiii		75%	
4Bi	4B	0%	***Demand-controlled ventilation*** **(supply and return)** and heat recovery with high and low rates (30%/100% BBR for dry rooms, 100%/130% for wet rooms) controlled by threshold setpoints of carbon dioxide[1] in dry rooms and relative humidity in wet rooms[2]. All dry zones set to one sensor in largest volume living space.
4Bii		50%	
4Biii		75%	

Note: [1] *(Borlänge Energi, 2020)* [2] *(Kim SW et al., 2007; Dietzin L. et al., 2020).*

By running total twenty-four variant cases in a whole year duration, the study intention is to assess potential corresponding impacts from aspects of IAQ, energy consumption, and thermal satisfaction. The simulation was conducted using the IDA Indoor Climate and Energy (IDA ICE). The formula expression of CO_2 emission generated from human respiration is as following (EQUA, 2020a):

$$CO_2\ Emission = 17 \times SUM_{i=1,}\{ n_{Occ} \times Act_{[i]} \times MET_{[i]}\} / 3.6 \times 1.8 \qquad (1)$$

where, *nOcc* is the number of occupants in a zone; *Act* is the activity level of occupants and *MET* means the metabolic rate according to ISO 7730.

Error! Reference source not found. generally describes CO_2 emission balance from a person in a zone with the unit of [mg/s]. CO_2 is a typically good indicator of the indoor air quality in residential buildings. Within this study, it does not take into account the age (size) of the occupants, and the CO_2 level in the outside air is fixed at 400 ppm while the CO_2 control threshold is setting at 1150 ppm for the adequate air quality (EQUA, 2020b).

Concerning the thermal comfort, the criteria of IDA ICE considers the conformance in living spaces only to the thermal comfort ranges defined in EN 15251:2007. As well known, the virus of COVID-19 is spread primarily through close contact with an infected person via respiratory droplets from surroundings. Hereby, there is a raised criteria demand in evaluating the ventilation effectiveness, which is with an additional concept to measure how quick a ventilation strategy can bring in fresh air from the outside through mechanical and/or natural means to dilute human and product generated air pollutants. In this study, the indicator of air age aims to measure on how long an average air molecule has spent in the building. If a zone is ventilated by outside air only and is in steady state, this number is calculated via the reciprocal of air change per hour. And the age of air measure takes account also of air that has aged in neighbouring zones (EQUA, 2020b).

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Result and analysis

The results are categorized into two main aspects, as the mechanical ventilation system under normal operation and other operations caused by confinements.

Mechanical ventilation system comparison under normal operation mode

By running eight cases in a whole year duration under normal operation schedule, total four brief mechanical ventilation types have been firstly assessed. *Table 3* clearly depicts the overall performance into six criteria. In terms of energy and associated results, it is intuitive that they are in proportional to the gross mechanical airflow rate under the constant air volume operation (CAV). Generally compared to the delivered heating energy of the base case, the energy performance improvements are approximate 13% for ***CAV Occupancy controlled ventilation*** **(exhaust only)**, 23% for ***Demand-controlled ventilation*** **(exhaust only)** and 36% for ***Demand-controlled ventilation (supply and return)***, which are in accordance to the dependency levels of demand-response approach. Even providing the same amount of the gross mechanical airflow during the occupied time as 1Bi, 3Ai and 4Ai, 4Bi has the best performance in 54% in zone heating load reduction, 45% in the delivered heating energy saving, 54% in the CO_2 emission drop.

In terms of thermal comfort, the studied building presents original design problems under the base case ventilation system installation, whose thermal dissatisfaction ratio is greater than the acceptable range of 10%, especially due to greater air tightness and larger southern facing glazing in the biggest living room. The further variant types further exhibit the thermal performance deterioration, which is expected to be a growing design problem under future climate change without help of mechanical cooling. Despite the same gross mechanical airflow rate as that in 1Ci, 2i fulfils the freshest air quality with an appropriate thermal dissatisfaction, meanwhile having a much better energy performance. The percentage of total occupant hours with thermal dissatisfaction is accounted when the operative temperature is outside the comfort range. The comfort range is further calculated based on the outdoor running mean air temperature as described in EN 15251 during the occupied period only.

Table 3 Overall comparison of proposed mechanical ventilation strategies under normal operation mode

No.	***Delivered Heating Energy, kWh***	***CO_2 emis-sion, kg***	***Zone heating load, kWh***	***Thermal dissatis-faction***	***Mean air age, hr***
1Ai	6781.2	1304.5	11401.8	27%	2.68
1Bi	6767.7	1308.3	11339.1	28%	2.7
1Ci	7827	1566.7	13468.1	24%	2.63
2i	5924.1	1137.2	9513.4	31%	2.63
3Ai	5195.9	949.9	8312.7	35%	4.14
3Bi	5212.36	955.6	8389.7	35%	4.08
4Ai	4368.5	718.1	6142.8	37%	4.32
4Bi	4337.4	715.6	6103.8	38%	4.32

Impacts from confinements levels

In this part, the proposed mechanical ventilation types are further investigated under two confinement levels. Comparing to *Table 3*, *Table 4* and *Table 5* clearly demonstrates overall decreasing trends in terms of energy saving and emission reduction. In terms of Delivered Heating Energy, ***CAV Occupancy controlled ventilation*** **(exhaust only)** turns to gradually lost energy conservative advantages with saving rates from 13% under the normal operation mode to 4% under the 'strict' lock down mode. Meanwhile ***DRV*** **(exhaust only)** and ***DRV (supply and return)*** have slight fluctuations around the individual energy saving percentages as those shown in *Table 3*. Owning to raised occupied time under two confinement levels, thermal dissatisfaction performance continuously deteriorate within the unacceptable category. Regarding the air freshness, ***Fixed exhaust ventilation*** category generally keeps steady lowest mean values of air age around 2.12- 2.7 hr. ***CAV Occupancy controlled ventilation*** **(exhaust only)** category hovers around 2.8-3 hr, and the category of ***DRV*** **(exhaust only)** seems to be unstable with fluctuations around 3.79-4.3 hr, while the category of ***DRV (supply and return)*** presents improving development around 4.14-4.32 hr. The differences mainly lie in varied air rate in ventilation and different targeted zones. It should be paid special attention to the thermal dissatisfaction percentage over 15% and the mean air age over 2.5 hrs (L. Hamner et al., 2020).

Table 4 Overall comparison of proposed mechanical ventilation strategies under 50% lock down mode

No.	**Delivered Heating Energy, kWh**	**CO_2 emis-sion, kg**	**Zone heating load, kWh**	**Thermal dissatis-faction**	**Mean air age, hr**
1Ai	5949.9	1100.9	9053.7	34%	2.70
1Bi	5925.6	1093.9	8973.1	35%	2.71
1Ci	6926.4	1337.7	10992.7	30%	2.12
2i	5576.7	1024.1	8247.3	36%	3.00
3Ai	4741	835.6	6909.9	40%	4.30
3Bi	4211.9	683.5	5691.5	44%	3.79
4Ai	3742.1	543.6	4329.7	43%	4.22
4Bi	3702.5	540.7	4282.6	44%	4.22

Table 5 Overall comparison of proposed mechanical ventilation strategies under 75% lock down mode

No.	**Delivered Heating Energy, kWh**	**CO_2 emis-sion, kg**	**Zone heating load, kWh**	**Thermal dissatis-faction**	**Mean air age, hr**
1Ai	5670.8	1033.3	8264.3	36%	2.68
1Bi	5651.8	1031.6	8166.5	37%	2.68
1Ci	6645.4	1279.2	10152.8	32%	2.13

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2i	5457.1	987.2	7820.7	37%	2.83
3Ai	4700.9	831.8	6737.1	40%	4.03
3Bi	4325.2	723.6	5810	43%	3.9
4Ai	3536.4	480.8	3760.8	45%	4.15
4Bi	3702.5	540.7	3698.6	46%	4.14

Discussion

Nowadays under the recommended exhaust ventilation installation in Scandinavian region, natural airing hardly takes place spontaneously in airtight residential buildings. From another side, the unpredictable airing would have dramatic influences on existing balanced indoor air characteristics as well as other undesirable situations, such as time delay to rewarming and excess energy waste and noise. For this reason, the demand response ventilation offers well-established energy efficient ventilation option in Scandinavian region to satisfy both varied indoor climate conditions and the compulsory indoor requirements. Since the human sensory system is unable to register the majority of harmful air pollutants in an indoor environment, healthy ventilation gets more and more important especially in response to global health challenges such as the COVID-19 pandemic.

The demand response ventilation approach has been proved to possess a remarkable performance in terms of energy saving and emission reduction in this study. Under the emerging challenge, it has to confront more design considerations. Since a longer occupied home working time, it turns more internal gains into useful passive heat gains in reducing the original space heating loads during the heating season. By sacrificing some energy savings from this, it is possible for demand response ventilation approach to maintain a consistent overall indoor climate with extra guarantees in both thermal comfort and improved air quality. Due to the characteristics of home working, occupants are supposed to have distinct occupied places and activates varying from daytime to nighttime. That further infers that specific air quality requirements exist for various zones during several time periods. Given to these changed occupant behaviour patterns, it would result in diverse impacts on indoor climate accordingly. Considered to these new changes, it is suggested to divide the home spaces into primary occupied zones and secondary occupied zones. According to the supervisory control refinement in ventilation system, both precise controlling and energy conversation have the opportunity to be obtained simultaneously. In line with this thought, this study further explores implementations of the advanced ventilation strategies within demand response ventilation scope, effective air freshness measures have been listed, such as increased supply/return air flow rate, various demand-control signals, and displacement ventilation placement. The findings also refers to that the thermal comfort condition is varying greatly on others. The possible impacting reasons are the external exposure of the demand responded room, accuracy and deadband inside demand control algorithms, and indoor temperature variation caused by internal gains. Consequently, the subtle improvements in demand response ventilation control design can be suggested in precise sensor position, balanced thresholds of the controlled variable setpoints, the correct placement of either supply or return air terminals, commission and relevant control logic adjustment for simultaneous decision judgment.

Conclusion

This study explored the performance of different mechanical ventilation systems in a single-family house in response to the CVIOD-19. Four typical mechanical ventilation systems are studied under three different operation schedules. It aims to improve an advanced DRV solution that is able to contribute towards a better home-working environment in terms of prevention, preparedness, resilience and recovery in relation to pandemic outbreaks and other respiratory infections.

Within total twenty-four ventilation variant cases, the maximum energy saving from the total delivered heating energy can up to 3490 kWh per year, along with annual carbon emission reduction of 851 kg CO2e. However, due to different occupied hours under altered confinement levels, the percentages of occupied thermal dissatisfaction get worse from 24% to 46%. By looking into the air age status in the biggest room, living space, the mean annual air age differs from the shortest of 2.12 h to the longest of 4.32 h. In general, DRV approach type has been proved to possess a remarkable performance in terms of energy saving and emission reduction, however it has to confrontation more challenge under the challenge as COVID-19 pandemics. By sacrificing certain amount of energy savings that can be compensated from more internal gains, it is possible for the DRV approach to maintain a consistent overall indoor climate with extra guarantees in both thermal comfort and improved air quality. The subtle improvements can be suggested to have supervisory control refinement in ventilation system, effective air freshness measures, and other impacting reasons, which would be external exposure of the demand responded room, accuracy and deadband inside demand control algorithms, and indoor temperature variation caused by internal gains.

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