IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Comfort-oriented control strategies for decentralized ventilation using co-simulation

To cite this article: N Carbonare *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 032018

IOP Conf. Series: Materials Science and Engineering **609** (2019) 032018 doi:10.1088/1757-899X/609/3/032018

Comfort-oriented control strategies for decentralized ventilation using co-simulation

N Carbonare[1,2,*], T Pflug[1], C Bongs[1] and A Wagner[2]

[1] Fraunhofer Institute for Solar Energy systems, Heidenhofstr. 2, 79110, Freiburg, Germany
[2] Karlsruhe Institute of Technology, Englerstr.7, 76131, Karlsruhe, Germany
[*] nicolas.carbonare@ise.fraunhofer.de

Abstract. Mechanical ventilation systems have acquired relevance in the past years in order to guarantee the hygrothermal comfort and indoor air quality (IAQ) in highly retrofitted residential buildings. The optimization of control strategies could provide a solution to this existing trade-off between energy efficiency, hygrothermal comfort and IAQ. In this publication, we propose a co-simulation approach (using EnergyPlus and Modelica) and a mathematical approximation of the discomfort of the occupant (namely, quadratic for relative humidity and exponential for CO_2), and apply them to a demand controlled ventilation (DCV) scheme. Results show that this approach provides around 10% energy savings, while improving the thermal comfort, without compromising the humidity comfort or the IAQ. Finally, the developed functions could allow the control schemes to adapt to different occupant preferences, showing potential for future work.

1. Introduction

The impact of energy retrofits on occupants' satisfaction levels and indoor air quality (IAQ) is still under investigation, though there is clearly a trade-off between energy consumption, hygrothermal comfort and IAQ. Within this framework, the use of mechanical ventilation systems has acquired relevance as a potential solution to this problem [1].

One of the most investigated control strategies is demand controlled ventilation (DCV) [2], given the need to adjust the ventilation systems to the occupants' activities. The importance of an optimized control system was investigated by Laverge [3], whose results with DCV-exhaust system showed that about 40-55 % of ventilation heat loss reductions can be achieved at equivalent IAQ levels. In addition, Vasile [4] points out that dwellings showing lower IAQ are associated also with a higher energy consumption. In the case of centralized HVAC systems, the latest developments aim at comfort as a priority against energy efficiency [5]. Wall-integrated decentralized ventilation systems (DVS) are one possible solution for the renovation in residential buildings in Germany [6]. These systems offer new opportunities for roomwise and user adaptive control strategies, yet they offer nowadays rather simple solutions. The state-of-the-art strategies provide constant volume flow rates with three or four levels, or flow rates related to the CO_2 or humidity at best [7], being these typical indicators of IAQ in DCV schemes. To provide a flexible simulation approach, combining building and system models, the co-simulation couples the strengths of different environments, in order to reach reliable results [8].

Therefore, in this publication we propose a new DCV strategy, taking into account the potential comfort requirements of the user. This strategy is tested for wall-integrated DVS in a co-simulation environment, which is described in the next chapter. The results show potential for the enhancement of current control strategies on DVS.

2. Methodology

2.1. Building and HVAC simulation model

We selected a single dwelling of a typical German multifamily building (MFB) for this study. The characteristics were assumed based on the investigation from the project "LowEx im Bestand" [9]. The floor plan is illustrated in Figure 1 (left).

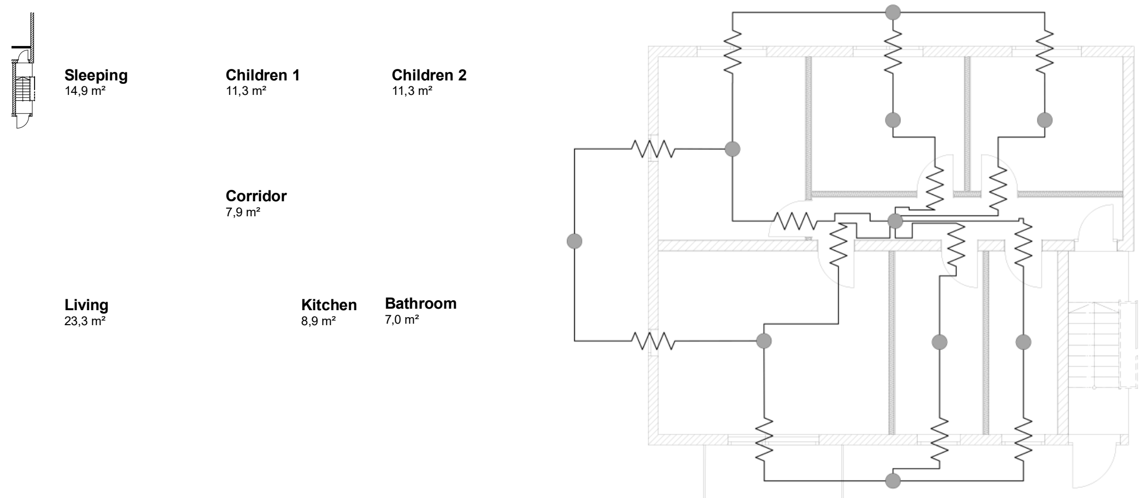

Figure 1. Floor plan of the building simulated (left) and airflow network model (right).

Regarding the thermal simulation, floor, ceiling and neighbour walls were modelled as adiabatic surfaces, as it is assumed that adjacent rooms have similar room temperatures. The U-values correspond to those of a renovated building (Table 1). The building was simulated using the open source widespread software EnergyPlus [10]. Air movement, infiltration and wind pressure were simulated applying the airflow network modelling (Figure 1 right). The heating system was ideally modelled, using the set points of the norm DIN EN 15251 [11].

Table 1. Building properties.

	Unit	Value
Exterior wall U-value	$[W.m^{-2}.K^{-1}]$	0.23
Interior wall U-value	$[W.m^{-2}.K^{-1}]$	1.30
Windows U-value	$[W.m^{-2}.K^{-1}]$	1.30
Infiltration n_{50}	$[h^{-1}]$	0.5

A full week was simulated. The time use schedule was taken from the ISO 18523-2 [12], assigning to the activities their corresponding loads of heat, moisture and CO_2 [13]. Other contaminants are not modelled. The window opening behaviour was modelled dependent on presence, indoor and outdoor temperature [14].

The DVS is a wall-integrated device with reversible fan. It works one period in supply mode (60 seconds), and then in exhaust mode. A thermal mass is used as a heat storage between supply and exhaust phase. The device was modelled in the programming language Modelica [15]. Figure 2 illustrates the mentioned device, with all the modelled components (fan modelled as a double component for both flow directions, heat recovery and pressure drop). Each room contains two of these DVS, each one having a maximum airflow of 46 m³/h.

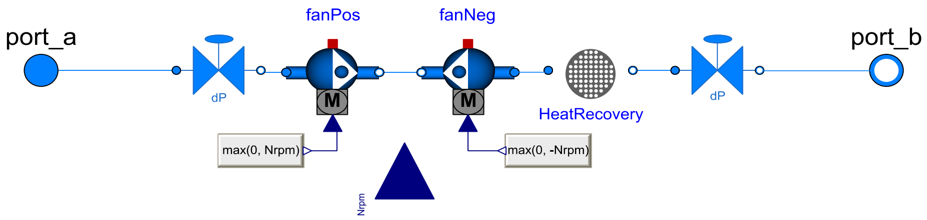

Figure 2. Wall-integrated ventilation device model in Modelica [15].

We coupled both model environments through the Functional Mock-up Interface (FMI) for co-simulation using python [16]. In this publication, the full week simulation, using one-minute time steps, lasts ten minutes on average.

2.2. Ventilation control

In order to maintain the desired IAQ and comfort level, the state-of-the-art control systems propose open-loop DCV strategies using steps or linear interpolation (*steps* and *linear* in the plots, respectively) with the fan speed [7, 17]. Considering the expected dissatisfaction described in the norm DIN EN 15251 [11], we propose in this publication that this dissatisfaction (*D*) due to the relative humidity can be approximated with a quadratic function, while the carbon dioxide concentration fits better the upper tier of a logit function [18]. The equations 1 and 2 define the proposed evaluation, and the Figure 3 compares the state-of-the-art and new methods respectively. We automatically assign humidity control to “humid” rooms (bathroom and kitchen) and CO_2 control to “dry” rooms (sleeping rooms and living room). Our proposal will be referred to in the plots in chapter 3 as *QuadLog*.

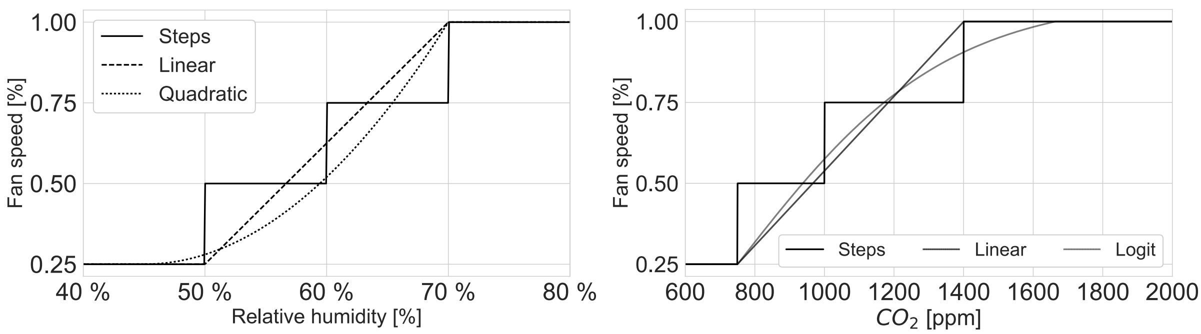

Figure 3. Control strategies for relative humidity (left) and carbon dioxide (right).

$$D_{RH}\,(RH) = k_1 \max(0; abs(RH - 40) - 5)^2) \tag{1}$$

$$D_{CO_2}\,(CO_2) = k_2 + \frac{k_3}{1+ex\,p(1-CO_2)} \tag{2}$$

Being:

- RH the room relative humidity in [%], and CO_2 the carbon dioxide concentration in [ppm].
- k_i different equation constants to shape the desired function (adimensional).

A second proposal is to assign the control strategy on each room with the highest dissatisfaction. This means, when the dissatisfaction due to relative humidity is higher than CO_2, this strategy is selected, and vice versa. We named this the “cost function” strategy (*Costfun* in the plots). The four mentioned strategies (*Costfun* against *Steps*, *Linear* and *QuadLog*) will be analysed and compared in the following chapter. The criteria investigated are energy consumption, comfort and IAQ.

2.3. Performance indicators

The energy consumption due to mechanical ventilation is defined as the electrical energy consumed by the fan, plus the heat losses due to the forced air exchange in a dwelling (Equation 3).

$$E\ [kWh] = \dot{V}\left(3.6\, SPI + \rho\, C_p\, \Delta T\right) \tag{3}$$

being:

- $\dot{V}$ the volume flow in [m^3.h^{-1}], and SPI the specific power of the fan, 0.35 [W.h.m^{-3}]
- ρ the density in [kg m^{-3}], and C_p the heat coefficient in [kJ. kg^{-1}.K^{-1}].
- ΔT the temperature difference between the room and the supply air, in [K].

Comfort and IAQ indicators are taken from the norm DIN EN 15251 and summarized in Table 2. The corresponding dissatisfaction values for each variable can be found on the norm. The effects of ambient temperature on the building are not analysed, since the simulation is in winter conditions. Therefore the ambient temperature is always under 10°C.

Table 2. DIN EN 15251 [11] indicators (Ambient temperature < 10°C).

Class	Air temperature [°C]	RH upper [%]	RH lower [%]	CO_2 [ppm]
I	21.75 < T < 24.1	50	30	750
II	20.75 < T < 25.1	60	25	900
III	19.75 < T < 26.1	70	20	1250
IV	19.75 > T; T > 26.1	>70	<20	> 1250

3. Analysis of results

3.1. Comfort

Figures 4 and 5 present the time distribution of the comfort classes from Table 2 related to RH and air temperature, respectively, during occupancy. Regarding the RH, the *Linear* and *Costfun* strategies present slightly better results than the other ones in the bathroom. In the kitchen, the *Steps* and *Costfun* strategies perform at best. Nevertheless, these differences are not significant (less than 5% in all cases) and all strategies provide an acceptable humidity control in humid rooms around 90% of the time. This does not consider that an occupant can open windows due to high humidity levels.

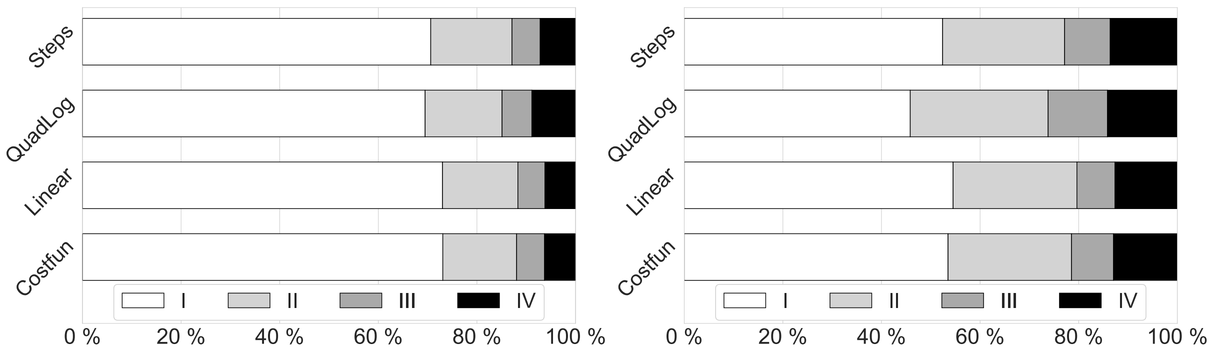

Figure 4. Relative humidity comfort classes in the bathroom (left) and kitchen (right).

In the case of the room air temperature, Figure 5 shows an overall advantage of the *Costfun* strategy. Even though the air temperature is not a part of the function, the proposed functions lower the air exchange rate when not needed, resulting in better indoor temperature comfort. Around 25% of the time, the sleeping room is in class IV, while in state-of-the-art strategies it reaches almost 40%. Similar behaviour can be observed in the children room 1.

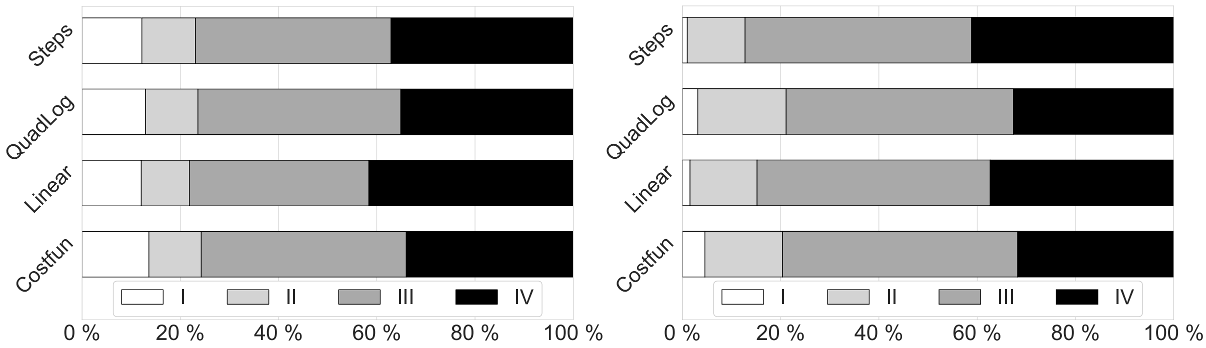

Figure 5. Room temperature comfort classes in the sleeping room (left) and children room 1 (right).

3.2. Indoor air quality

Analysing the resulting IAQ, the four compared strategies reach similar results. In the Figure 6, the distribution of the classes during the occupancy periods in two rooms is presented.

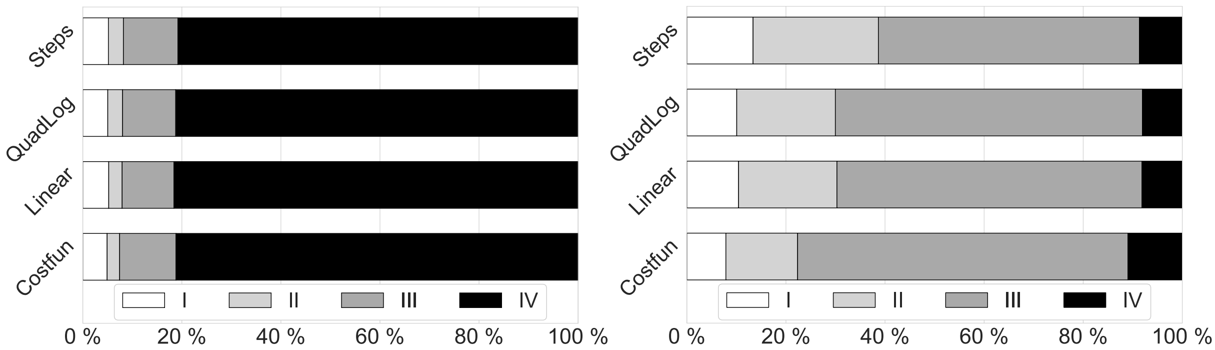

Figure 6. IAQ classes in the sleeping room (left) and living room (right).

Even though the fan works at full speed, the sleeping room presents around 80% of the time IAQ class IV. This means, the fans might be underdimensioned for this room, since the CO_2 concentration levels reach equilibrium at 1400 ppm (two occupants). Besides, in the living room the air class is under level IV around 90% of the time in all studied strategies. Overall, we can affirm that the different strategies perform similarly in terms of IAQ in the sleeping room, and the *Costfun* strategy performs slightly worse in the living room.

3.3. Energy consumption

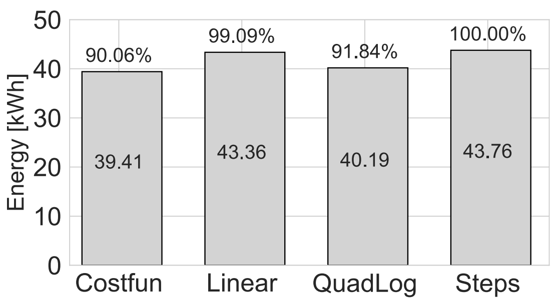

Figure 7. Energy consumption. Absolute values within bars, relative decrease above them.

As it can be seen in Figure 7, the energy consumption due to the forced air exchange is lowest in the cost function, due to lower airflow rates on average. For instance, taking as a reference the most widespread control on the market (*Steps*), the energy savings are 9.9%. The results also show that predefining humid and dry rooms undermine slightly the potential energy savings.

4. Conclusion and summary

We proposed two novelties in this paper regarding comfort-oriented control strategies for decentralized ventilation systems. First, we developed a quadratic approximation for RH discomfort and exponential for CO_2, respectively. Second, we applied them in a control system that selects the appropriate strategy by means of the higher discomfort. The results show energy savings around 10% in comparison with a reference state-of-the-art strategy, while at the same time providing better thermal comfort around 15% of the time, without strongly compromising the IAQ (5% worse at most) in comparison to conventional strategies.

The proposed dissatisfaction curves are norm-based, although they could be adjusted to individual preferences in real conditions. In future research, we expect to continue investigating comfort-oriented control strategies for ventilation and to test them in real buildings, to analyse their applicability. Other possible discomfort variables should be studied (such as noise or other relevant contaminants), as a possible path to enhance the proposed strategy. In addition, the dimensioning of the fans should be addressed in order to avoid to high CO_2 concentrations in the sleeping room.

Acknowledgement

The study presented in this paper is funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) under the reference FKZ03SBE0001A/B/C.

References

[1] Carbonare N, Coydon F, Dinkel A and Bongs C 2017 *Proceedings of 38th AIVC Conference*
[2] Rotger-Griful S, Jacobsen R H, Nguyen D and Sørensen G 2016 *Energy and Buildings* **121** 1–10
[3] Laverge J, van den Bossche N, Heijmans N and Janssens A 2011 *Building and Environment* **46** 1497–503
[4] Vasile V, Petran H, Dima A and Petcu C 2016 *Energy Procedia* **96** 277–84
[5] Kim S H and Moon H J 2018 *Building and Environment* **133** 246–64
[6] Mansurov R S and Rafalskaya T A 2017 *J. Phys.: Conf. Ser.* **891** 12156
[7] Pavlovas V 2004 *Energy and Buildings* **36** 1029–34
[8] Nouidui T S, Wetter M and Zuo W 2013 *13th Conference of International Building Performance Simulation Association* 3275–82
[9] Ebert B 2018 *LowEx-Bestand Analyse Abschlussbericht zu AP 1.1: Systematische Analyse von Mehrfamilien-Bestandsgebäuden* (Karlsruher Institut für Technologie)
[10] Crawley D B *et al* 2001 *Energy and Buildings* **33** 319–31
[11] Deutsches Institut für Normung e.V. and European Committee for Standardization 2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics **91.140.01** *(*15251*)*
[12] International Organization for Standardization 2018 Energy performance of buildings - Schedule and condition of building - zone and space usage for energy calculation. Part 2: Residential buildings *(*18523-2*)* 1st edn
[13] Firląg S and Zawada B 2013 *Energy and Buildings* **64** 372–83
[14] Schweiker M, Haldi F, Shukuya M and Robinson D 2012 *Journal of Building Performance Simulation* **5** 55–74
[15] Mattsson S E and Elmqvist H 1997 *7th IFAC Symposium on Computer Aided Control Systems Design, Gent, Belgium* 1–5
[16] van Rossum G 1995 *Python tutorial, Technical Report CS-R9526* (Amsterdam)
[17] Smith K and Svendsen S 2016 *CLIMA 2016 - 12th REHVA World Congress*
[18] Jokl M V 1998 *International Journal of Biometeorology* **42** 93–111