The influence of occupancy behaviour on the performance of mechanical ventilation systems regarding energy consumption and IAQ

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ABSTRACT

It has already been proven that a large portion of the energy consumption gap between simulations and reality is due to the occupant behaviour in buildings. The improving airtightness of buildings makes that Indoor Air Quality (IAQ) can no longer rely on air renewal through infiltrations, bringing the need of ventilation systems. Within this frame, an ongoing dissertation focuses on the relationship between occupancy behaviour and ventilation systems in low energy buildings. In this paper, focus is made on a high rise residential multifamily building in south Germany, which has been retrofitted and then measured for two years to obtain post-refurbishment information. The occupant's behaviour nature was captured in 27 dwellings by measurements of inside temperatures and window openings and applied to the dynamic simulation environment WUFI+. In addition, a presence estimation model was developed in order to represent user behaviour as close as possible to reality. Different behaviours' scenarios (concerning window opening, temperature set point, presence, activities) were combined with different control strategies for mechanical ventilation systems, with the aim of analysing the impact of these variables on the energy consumption, thermal comfort and IAQ. The results show that there is a significant energy savings potential that can be achieved regarding to the occupant behaviour, and that the most challenging issue is the trade-off between these energy savings and maintaining healthy environments with higher IAQ. The challenges of the next generation of control strategies for ventilation systems will be to provide high flexibility to make the systems compatible with different user behaviours.

KEYWORDS

Ventilation systems, Occupant behaviour, Indoor Air Quality, Energy-efficient buildings, Simulation

1 INTRODUCTION

The world's increasing energy demand has led in the last twenty years to an increasing interest on energy efficiency. The efforts towards the energy consumption reduction in the residential sector have brought up the retrofit of buildings as a solution in European countries. The high air tightness is a characteristic of these retrofits, as it contributes to reduce the heating energy consumption. Within this frame, mechanical ventilation systems acquired relevance to keep a desirable indoor air quality (IAQ) in retrofitted buildings.

On the other hand, the evaluation of these aforementioned technologies reveals that the performance is lower than expected in practical applications. It is already clear that the diversity of the occupant plays a key role on this underperformance (Hong et al., 2016).

This paper aims therefore at studying the relationship between mechanical ventilation technologies and the role of the occupant in low-energy buildings through building simulation. It will contribute to set the ground for further research about the interaction between ventilation systems and OB, with the overall objective of reducing the gap between predicted and observed energy performance, while aiming at guaranteeing an acceptable IAQ and thermal comfort.

2 METHODOLOGY

The modelling of the OB represents a key step on this study, as it is the source of diversity, which influence on ventilation systems will be studied. Thus, it results of utmost importance to describe it as precisely as possible, through a combination between measurements and estimation methods. To carry out the study, measurements from a 16-storey multifamily building in South Germany (retrofitted to passive house standard in 2011) were taken, observing the behaviour of the occupants particularly in 27 dwellings (Kagerer et al., 2013). The aim is to capture the diversity of the occupant's behaviour in this building, and to apply it to simulations on a low-energy dwelling to analyse its effects on the performance of the ventilation system.

2.1 Occupancy Behaviour modelling

Initially the goal was to determine how the OB can be represented regarding the inputs of the simulation. The variables that will be taken into account are window opening behaviour, temperature set point and internal gains (heat, moisture and CO_2). Window opening and internal temperature were measured in the dwellings every six minutes, and the internal gains were estimated taking the measurements of heating power, domestic hot water and electricity consumption. The dependency of window opening profiles on ambient temperature is neglected by utilizing the measured outdoor conditions as input for weather data.

Due to the wide range of OB, the first step was to perform a statistical analysis of the measurements regarding window opening and indoor temperature. The aim was to obtain typical patterns of behaviour of both variables, grouping the similar ones into clusters. A hierarchical clustering method was selected and applied, taking into account the optimal number of clusters for each variable. The analysis is performed as if both variables (indoor temperature – IT – and window opening – WO) were independent.

The window opening behaviour is then clustered and grouped into six main behaviours, whereas in the case of indoor temperature three clusters were modelled. To illustrate this procedure, the figure 2-1 shows the yearly-averaged hourly profile for each dwelling, grouped into their cluster category. It can be clearly observed that each window opening profile has strong similarities with others of the same cluster and differences with those from the other clusters. The table 1 summarizes the evaluated alternatives in the simulations.

Six different random profiles were selected, considering one case per WO cluster and two from each IT cluster, which will be used as inputs of the simulation software. In the case of the indoor temperature, the set-point for heating devices was defined taking into account these differences among the OB. The simulation procedure will be described in the next chapters.

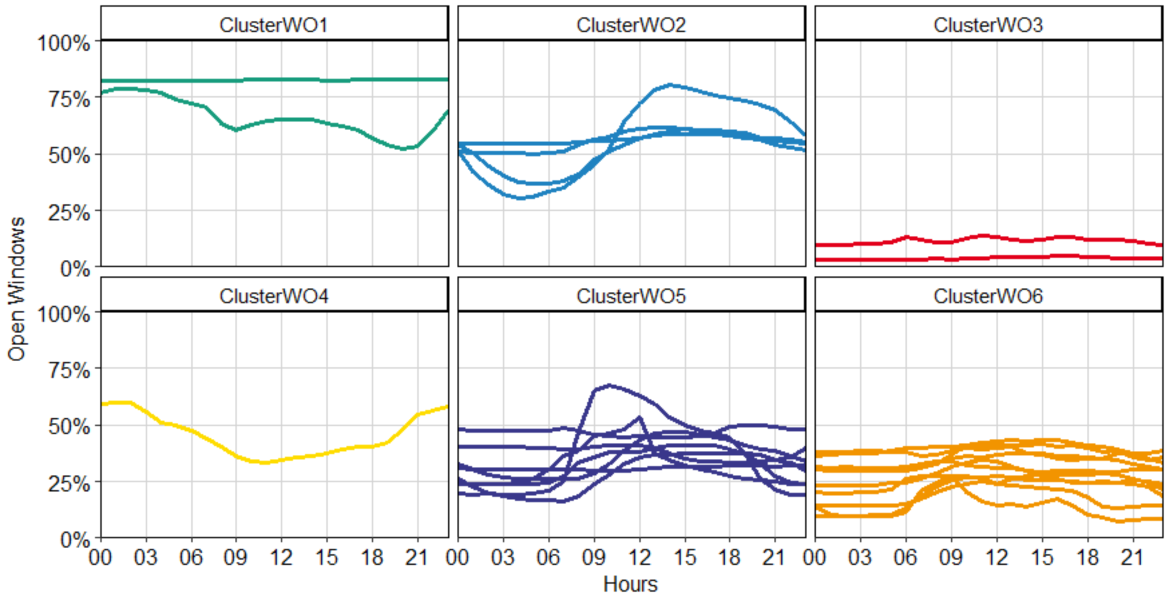

Figure 2-1: Window opening clusters

Table 1: Clusters characteristics

Simulation name	Window Opening	Indoor Temperature	Number of occupants
C1-1	Cluster WO1	Cluster IT1	1
C2-2	Cluster WO2	Cluster IT2	1
C3-3	Cluster WO3	Cluster IT3	1
C4-3	Cluster WO4	Cluster IT3	2
C5-1	Cluster WO5	Cluster IT1	2
C6-2	Cluster WO6	Cluster IT2	2

2.2 Presence and internal gains estimation

The variation of the internal loads can have an effect equal to the variation of the outdoor temperature in low-energy buildings (Johansson et al., 2011). In addition, according to Firlag (Firląg and Zawada, 2013) the internal loads are much lower than stated in norms. This produces an underestimation from the heating energy consumption, since the contribution of the internal heat sources is lower than expected. Andersen (Andersen et al., 2016) highlighted the importance of proper modelling of CO_2 and moisture sources in residential environment. Thus, it results of importance to estimate the internal loads dynamically. Some of them are related to the presence of the occupants, like the heat emissions of human metabolism; others, like the moisture gains from plants, are constant. As the presence was not measured, an estimation model was suggested to be developed, based on the measurements of window openings and instantaneous electrical power.

A literature review was carried out before defining the rules, in order to assess the current advances in the matter of presence estimation. These models attempt to build the other way round of the estimation: through the number of occupants and highly detailed stochastic models they estimate first if the dwelling is occupied or not, and then the activity the occupant performs, obtaining a 100% simulated electrical and heating load profile for a house. The main different amongst them is the number of states: while (Aerts et al., 2015) proposed a three state model (Present active, present passive or absent), others proposed a two-state model (active or passive in (Fischer et al., 2015), present or absent in (Kleiminger et al., 2013). In this case, the presence estimation model will be a three-state model, as the internal heat gains are affected by passive or active status of the occupants.

Therefore, a set of assumptions and rules were set in order to obtain the estimation model. Given that the measurements are taken every six minutes, four periods are considered at every time step (24 minutes). That means, for each calculation at, for example, 11:00 AM, the results of the activity between ± 2 periods are observed (10:48 AM – 11:12 AM). Since the windows are seen as a change of state, the standard deviation within these four periods is calculated. The instantaneous electrical power is relevant when it overcomes the stand-by operation value for a relevant period. In that sense, the mean is calculated in the observed range and then contrasted to the stand-by pre-calculated value. The result of an estimation model on a typical day for a random dwelling can be seen in the figure 2-2 (left side). Worth to say, a value of 1 means "active" state, 0.5 is "passive" (sleeping) and 0 is "absent".

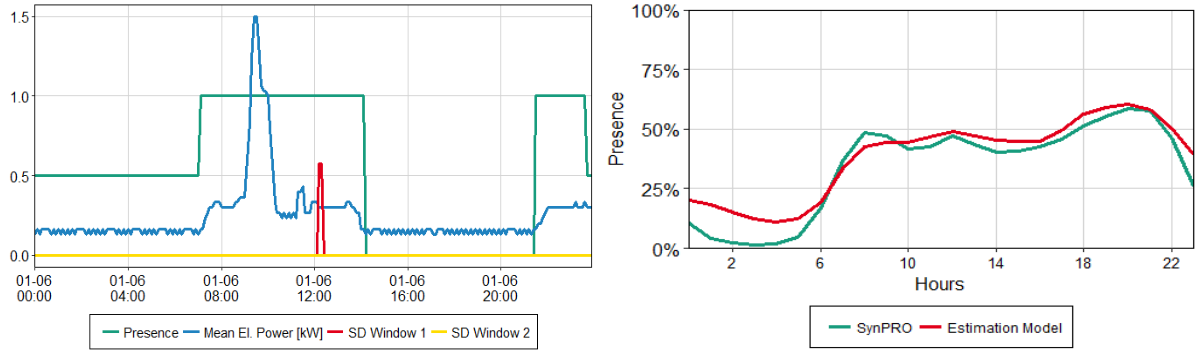

Figure 2-2: Presence estimation model (left) and validation (right)

To allow a cross validation of the proposed presence model, three separate multifamily buildings with six dwellings each were simulated with the tool SynPRO (Fischer et al., 2016), in which individual heating, DHW and electricity load profiles are generated stochastically. As inputs for the profile generation, similar social background and building envelope characteristics to the monitored building were selected, in order to obtain a representative occupant profile. The figure 2-2 (right side) compares the monthly-averaged hourly presence profiles for both simulations and estimation models.

The SynPRO profile fits the proposed model. It is worth mentioning that the drawn simulated profile is divided through the average number of occupants, in order to obtain a percentage value of the occupancy state. It is also relevant that the absent and passive state in the developed model were merged into only one (not active) to make it comparable with SynPRO simulation. Further cross validations of the model in comparison with other publications (Aerts et al., 2015; Kleiminger et al., 2013) were successfully carried out.

Besides the internal gains associated with the different activities, it is unneglectable that the room, in which these take place, plays also a role. The application of Agent-based Models to residential environments is still in development and has not yet reached enough interest from researchers (Zhang and Jia, 2016), as multi-occupant models with multi-space possibilities are still found to be weak in reproduction and prediction. Thus, an approximation was proposed here by defining rules and making assumptions about the occupants' movement. The last step refers to the determination of the internal loads. The general structure was built following these publications (Firląg and Zawada, 2013; de Gids W.F. and Wouters P., 2010). These were defined basically considering heat, moisture and CO_2 loads. There were no internal loads assigned to storage room and corridor. The table 2 presents a summary of the assumptions taken to build the whole internal gains map. The category “others” is associated namely with heat absorption by evaporation (wet towels, for example) and heat losses on heating and DHW distribution systems.

Table 2: Internal loads summary

Category	Convection heat [W]	Radiation heat [W]	Humidity [g/h]	CO_2 [g/h]	Observations
1 Adult - Active	80	40	45	40	
1 Adult - Passive	60	30	25	20	
Appliances	95% consumption		0	0	Surface distributed
Washing machine	25% consumption		200	0	Bathroom
Dishwasher	25% consumption		200	0	Kitchen/Living room
Cooking	600	200	500	0	12-12:30 & 18-18:30
Shower	0	0	1% consumption	0	
Plants	0	0	75	Neglected	Surface distributed
Others	50	25	15	0	

2.3 Simulation

The simulation is based on the floor plan of one dwelling of the refurbished building (Figure 2-3) and it is assumed to be 10 m above ground level. The selected dynamic simulation environment is WUFI+ (Pazold and Antretter, 2012).

Regarding the initial simulation assumptions, the floor, ceiling and internal walls will be modeled as adiabatic surfaces, as it is assumed that the neighbor dwellings contain similar room temperatures. The external wall consists of 16 cm EPS isolation, resulting in a total thickness of 37.5 cm and a U-value of 0.19 W/m^{2}K. The windows are modelled with a U-value of 1.2 W/m^{2}K and a frame factor of 0.71. Table 3 summarizes the thermal characteristics of the dwelling.

Table 3: Building characteristics of the simulations

Building characteristics	Unit	Value
Outer wall U-value	[W/m^{2}K]	0.19
Inner wall U-value	[W/m^{2}K]	0.92
Windows U-value	[W/m^{2}K]	1.20
Frame factor	[-]	0.71
Windows g-value	[-]	0.51
Infiltration rate n50	[1/h]	0.21
Leakage exponent	[-]	0.61
Leakage coefficient	[m^3/h Pa]	1.03

The inputs of window opening and temperature set point are independent from the outdoor ambient conditions and will be taken directly from the measured data. It is assumed that the driving forces associated with external ambient conditions are coherent, since the weather data used for the simulation is also measured from Freiburg in the year 2013.

Regarding the heating and ventilation systems (HVAC), they are modelled as ideal, meaning that the software responds immediately to meet the heating demands, representing therefore the heating energy demand and not the performance of a specific facility. On the other hand, ventilation systems are also ideally modelled, and so are the different control strategies approached on this study. The assumed heat recovery efficiency is 80 % in all cases.

Regarding shading devices, there is no shading accounted on the living room, whereas on the bedroom is set to 0.1 (10 % sun exposure) when sleeping (R-value = 0.2 W/m^{2}K). Taking into account the internal doors (relevant for multizone airflow model), the living-sleeping room door was set to 0.2 (opening rate) except while sleeping, when it is set to 0. This is also valid for the corridor-bathroom door (while presence in bathroom). The corridor-storage room door is neglected and set permanent to closed state.

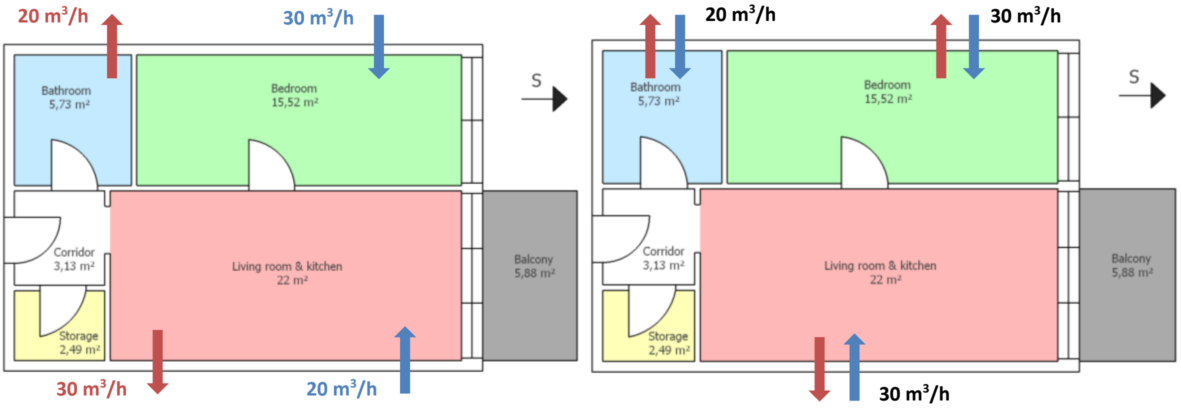

Figure 2-3: Simulated floor plan. Centralized system (left) and decentralized system (right)

In total, 48 simulations were carried out, selected according to the six clusters defined on table 1, and taking into account the following ventilation systems concepts (evaluated with and without heat recovery systems – HRC):

- Cen_CAF: Centralized ventilation with constant volume flow (v = 50 m^3/h)
- Dec_CAF Decentralized ventilation with constant volume flow (v = 80 m^3/h)
- Dec_RHu: Decentralized ventilation with relative humidity control
- Dec_CO2: Decentralized ventilation with CO_2 control

In the case of centralized ventilation systems, the airflows were taken from the reference building. The control strategies are defined with the following ventilation rates into four steps, and then illustrated in the figure 2-4:

- 10-20-30-40 m^3/h in kitchen/living room and bedroom
- 5-10-15-20 m^3/h in bathroom

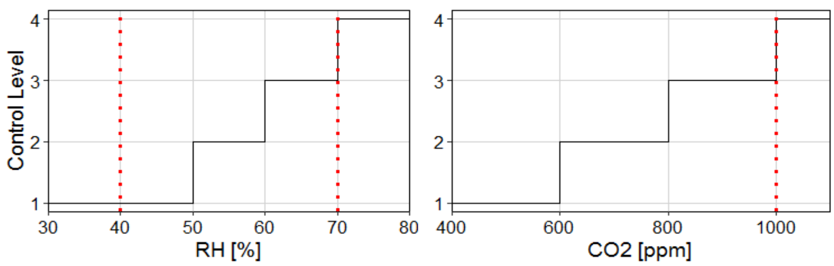

Figure 2-4: Ventilation control systems

2.4 Performance indicators

The performance indicators are defined following the work of Coydon (Coydon, 2015):
Energy performance:

- Heating demand due to ventilation, natural and mechanical [kWh/m^{2}a]
- Electricity demand of the fans [kWh/m^{2}a]

Hygrothermal comfort:

- Average temperature difference between indoor and supply air (1)
- Average relative humidity under 40% (2)

Indoor air quality:

- Average exposure to CO_2 concentrations above 1000 ppm (3)

$$\Delta T_{comf} = \frac{\sum \max\left(0; T_{in} - T_{sup}\right)}{presence} \quad (1)$$

$$\Delta RH_{comf} = \frac{\sum \max(0; 40 - RH_{in})}{presence} \quad (2)$$

$$\Delta CO_{2\text{-}IAQ} = \frac{\sum \max(0; C_{CO2} - 1000\ ppm)}{presence} \quad (3)$$

Given that the simulation does not allow introducing specific fan power (SFP), it will be calculated separately following typical industrial standards, adopting the values of 0.4 Wh/m³ for the systems with HRC, and 0.15 Wh/m³ for the cases without HRC.

3 DISCUSSION OF RESULTS

3.1 Energy consumption

The figure 3-1 illustrates the way heat recovery influences the energy consumption related to mechanical ventilation systems. Not only there is a reduction on energy consumption, but also a lower variation among the different control strategies (summarized in one box) can be observed. Heat recovery provides an average energy saving of 74% on mechanical ventilation systems and 37.3% considering also heat losses on natural ventilation.

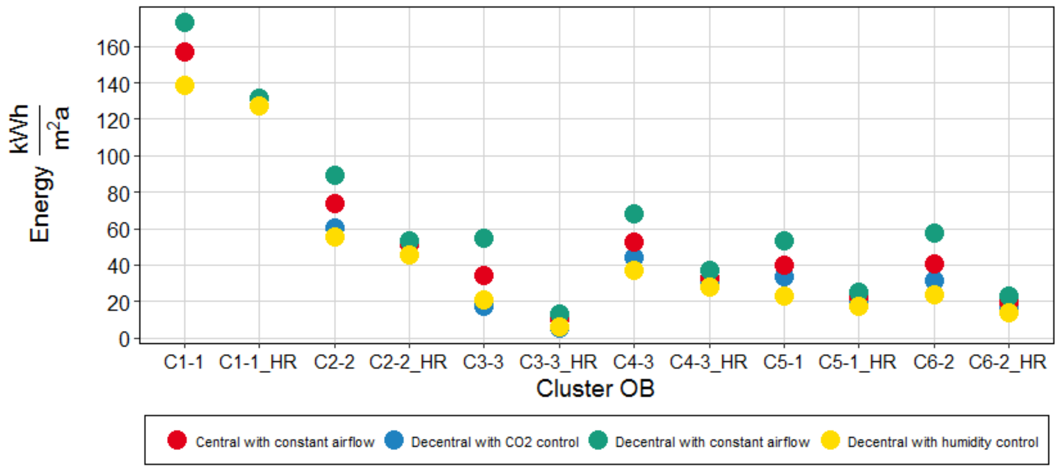

Figure 3-1: Final energy consumption with and without heat recovery

The analysis will focus therefore only on simulations with heat recovery. Figures 3-2 and 3-3 illustrate the total energy demand regarding control strategies, different occupancies and natural ventilation. Even though there is energy optimization potential, the overall energy consumption that predominates is led by natural ventilation, dependent on the WO behaviour of the occupant. This is correspondent with the clustered profiles presented on the figure 2-1. The cluster WO3 (lowest WO) consumes in every case at least seven times less energy due to ventilation than cluster WO1 (highest WO). This pictures the influence of the OB on the performance of ventilation systems and highlights the importance of studying it and developing techniques of inducing an “energy saving” behaviour.

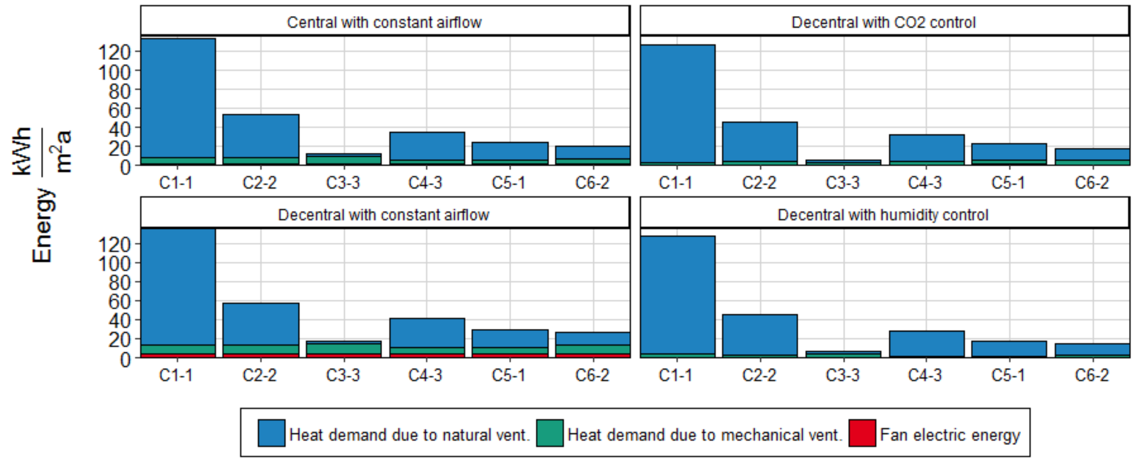

Figure 3-2: Final energy consumption due to ventilation

Moreover, focusing on mere mechanical ventilation, the optimization potential can be easily identified. The figure 3-3 shows that the energy consumption of the controlled systems is always lower than for the constant airflow cases. The simulations with only one occupant (clusters WO 1-3) present their lowest consumption with CO_2 control (2% lower than RH), whereas the ones with two occupants (WO 4-6) have lower consumption with RH control (45% lower than CO_2). It results also that the energy savings provided by a proper control system (70.1 % for mechanical ventilation, 22.7 % for final energy demand) is on a similar range as the savings obtained by the implementation of heat recovery (74 % and 37.3 %).

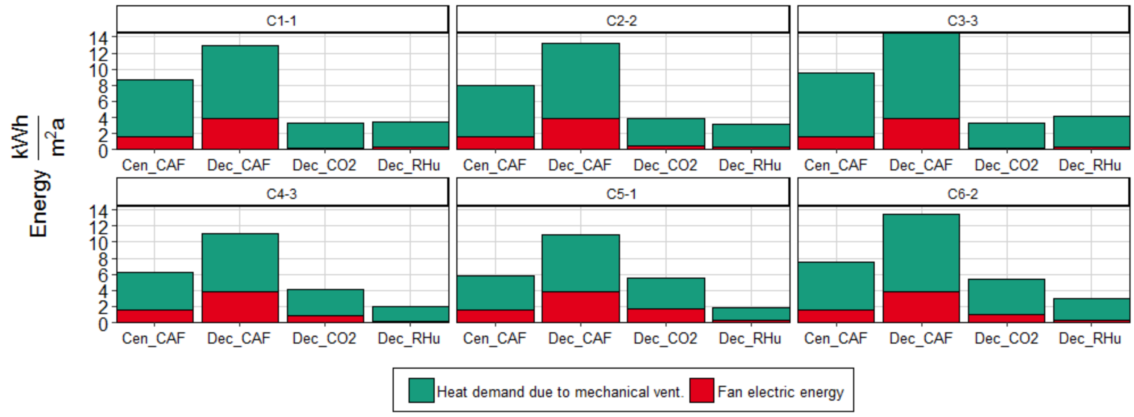

Figure 3-3: Final energy consumption due to mechanical ventilation

3.2 Comfort and IAQ

Relative humidity and CO_2 indicators do not vary with heat recovery. Analysis is then carried out only with heat recovery. The figure 3-4 summarizes the performance indicators, while showing the final energy consumption due to mechanical ventilation. Observing the comfort temperature difference, the value is directly related to the WO behaviour, as natural ventilation also contributes to this difference.

Considering relative humidity, it is noticeable that the constant airflow systems provide higher air flows, causing draught in the dwellings. The general WO behaviour combined with the ventilation strategies resulted in no case where RH stayed always above 40%. The cluster 1-1 is the evidence that a higher WO leads to a lower hygrothermal comfort and undermines the influence of the ventilation control systems on RH comfort. The cases with two occupants lead to better comfort results, as the humidity internal loads are higher, providing an average value closer to 40%.

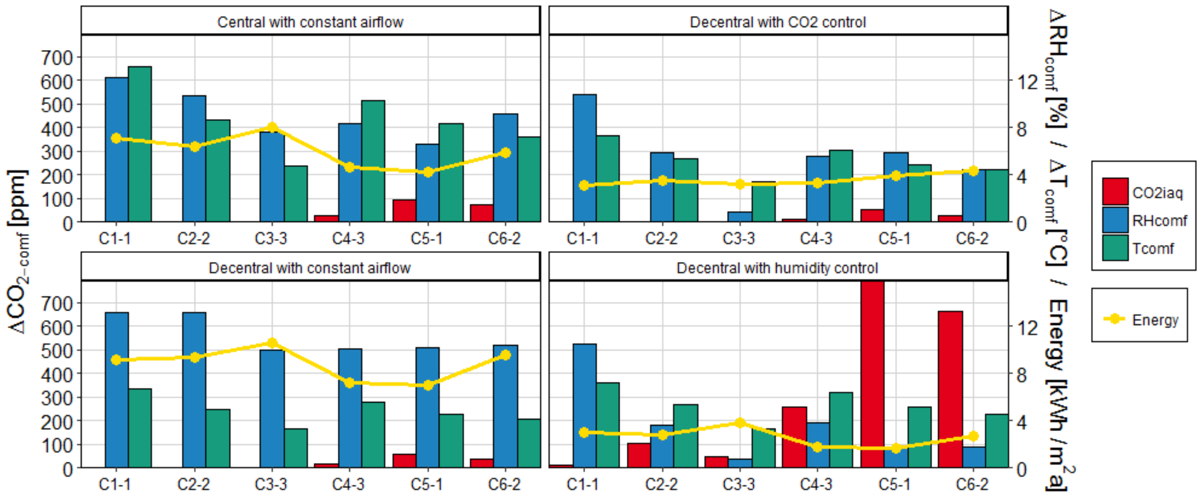

Figure 3-4: Performance indicators and energy consumption

Regarding CO_2, it is almost not an issue in dwellings with only one occupant (only with RH control system). In dwellings with two occupants, no control system was able to keep always the CO_2 level under the set maximum value, and the CO_2 control system reaches the same comfort and IAQ performances as the constant airflow cases, but lowering the energy consumption. The cases with two occupants lead to worse IAQ results, as the CO_2 internal loads are much higher, resulting then in higher energy consumptions and average CO_2.

The trade-off between the energy consumption, thermal comfort and OB is clear, in particular for the dwellings with two occupants. There is almost no case where the three variables present their most acceptable values at the same time. It is remarkable though, that the Cluster 3-3 presented the best results of the study, with rather high comfort standards and low energy consumption. Needless to say, it is the occupant with lowest WO. The fact that only one occupant lives there plays also a role in the acceptable IAQ performance, as the internal gains are considerably lower as in an apartment with two occupants.

4 CONCLUSIONS

This work presents the results of a simulation of a low energy building, focusing on the occupancy behaviour and ventilation systems. Different OB variables were captured through measurements on a low-energy multifamily building in South Germany; others were estimated through model development. The application of these models into a dynamic simulation environment contributed to a results analysis, where a trade-off between energy consumption, hygrothermal comfort and IAQ could be identified. Results are highly dependent on the OB, having a stronger influence on the energy consumption than the ventilation control system, which also shows optimization potential.

As for future research, it would be interesting to compare cases of low WO frequency and higher number of occupants, to see to what extent the optimal case of the cluster C3-3 and CO_2 control system is an “optimization”, rather than a result of low internal heat gains. In addition, although several estimations were found on the literature, the issue regarding the different internal loads should be further addressed and become a subject of research due to its importance on the building simulation and its lack of precise knowledge among the available models in the area. Centralized ventilation concepts with different control systems should be also studied. Furthermore, the next efforts will focus on the development of new simulation models of ventilation and control systems, in order to optimize the latter.

Last but not least, not only is capturing better the diversity of OB and its influence a challenge, but also trying through technology to provide the users a better understanding to generate a culture of "energetic behaviour", to reduce their impact on the current energy consumption models.

5 ACKNOWLEDGEMENTS

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