

# Investigation of a multizone building with HVAC system using a coupled thermal and airflow model

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**Abstract.** In building energy simulations, the air infiltration and interzonal airflow are generally either not considered or calculated oversimplified. However, the effects of air infiltration and building airflow have an impact on the thermal comfort and the building's energy load. The various zones in multi-zone buildings, the operation of windows, doors and mechanical ventilation make the system's analysis complex and challenging. Building airflow affects pressure, temperature and moisture differences. Therefore, this study investigate the airflow inside a multizone building with changing user behavior, using a coupled building and system energy simulation. A decentralized air-only HVAC system provides the ventilation system with a control strategy, which variably adapts the airflow to the load in the individual zones. The effects of the air infiltration, interzonal airflow and mechanical ventilation in the building are investigated with a node and link network in TRNSYS using the airflow model TRNFLOW (COMIS). Investigating different variations of the ventilation rates and building's airtightnesses, the results are shown by comparison with a reference model without airflow simulation. Finally, this study shows a comprehensive approach at low computational costs, determining the air quality, the thermal conditions and the airflow in a multizone building using an HVAC system.

## 1 Introduction

### 1.1 Motivation and goals of the study

Various studies have shown that air infiltration and interzonal airflow within multizone buildings have a considerable influence on the thermal conditions and air quality. The uncontrolled airflow causes higher energy demands leading to higher costs and eventually to discomfort.

In building energy simulations, the air infiltration and interzonal airflow are generally either not considered or calculated oversimplified. The various zones in multi-zone buildings, the operation of windows, doors and mechanical ventilation make the system's analysis complex and challenging. The building airflow affects the pressure, temperature and moisture balance. In this study, the presented method allows to simulate building airflow and thermal conditions including system technology with relatively low computational effort.

### 1.2 State of the art and relevance

Building energy simulations are generally used to determine the annual energy demand of buildings and HVAC systems. Due to the high complexity and the duration of the simulations, the airflow outside and inside the building are usually considered simplified or

completely neglected. In complex buildings, for example, the zones are considered as airtight to each other, which means that the interzonal airflow through open and closed doors is not taken into account.

However, the effects of air infiltration and building airflow have an impact on the thermal comfort and the building's energy load. Approximately 25 – 50 % of the energy load is due to air infiltration and ventilation [1]. Multizone airflow models evaluate the airflow rate and direction into, out of and through the building. The ventilation software uses mass flow and pressure equations to calculate the infiltration through leakages, the interzonal airflow and the contaminant transport. There are several multizone airflow simulation programs available. Compared to the beginning of multizone airflow simulations, the development of programs for the mentioned phenomena resulted in numerous commercially and freely available software. The AIVC guide by Orme [2] describes several programs for the airflow modeling including COMIS. COMIS and CONTAM offer comparatively the best possibilities to simulate airflow distribution for a broad range of cases and boundary conditions.

In this study, COMIS is used for the airflow simulation. COMIS has the advantage to be used as an add-on tool to the thermal building model, for instance in TRNSYS with TRNFLOW, but also as a stand-alone program [3]. Several publications persist for the validation of the multizone airflow programs. Haghighat and Megri [4] studied the airflow distribution in a two-

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story high multizone building and investigated the consistency of the results between COMIS, CONTAM, AIRNET, BUS, and CBSAIR. The simulation was performed with a single set of temperatures and wind-induced pressures. They reported a "good" agreement between the different airflow programs. The predictions for the airflow rates and room pressures were within a range of 5 and 13 %. They also conducted tracer gas measurements on-site to validate the results with the two most common airflow programs, namely CONTAM and COMIS. They concluded that the results of these two programs and the on-site test coincide. Another study from Fürbringer [5] investigated several multizone airflow programs on their consistency. 14 different simulation programs were examined by five different laboratories and concluded that all the compared models provided the same data within a very narrow 8 dispersion band. All the models used similar algorithms and the simulations were performed with identical input data.

Nevertheless, the advantages of simulation programs are undeniable with the low cost and the easy access to different building models. Typical CFD simulations are unsuitable for multizone airflow calculations because a tremendous amount of data is required to simulate the different zones of the building with the high required level of detail. Therefore, multizone airflow models examine the infiltration, interzonal airflow and contaminant transport.

## 2 Simulation model and boundary conditions

### 2.1. Basics

Due to internal and external thermal loads, a heating or cooling demand usually occurs in a building zone. This thermal load  $\dot{Q}_{0,N}$  must be supplied to or removed from the zone in order to be able to meet the thermal requirements at any time. The temporal integral over a certain period of observation, usually one year, leads to the annual energy demand of a building zone. For the calculation of the energy demand, the parts for ventilation  $\dot{Q}_{vent}$ , infiltration  $\dot{Q}_{inf}$ , transmission through walls and windows  $\dot{Q}_{trans}$ , solar radiation  $\dot{Q}_{solar}$ , internal gains  $\dot{Q}_i$  as well as thermal flows through interzonal air exchange  $\dot{Q}_{cplg}$  are considered in the simulation model [6].

$$\dot{Q}_{0,N} = \dot{Q}_{vent} + \dot{Q}_{inf} + \dot{Q}_{trans} + \dot{Q}_{solar} + \dot{Q}_i + \dot{Q}_{cplg} \quad (1)$$

The building airflow through all zones, induced by pressure differences, is modeled by the mass balance Equation (2). The mass balance of a zone is therefore replaced by the power law [7]. The pressure distribution is calculated for all zones  $m$  and is influenced by the number of flow paths  $k$  in a zone.

$$\sum_{i=0}^m \left\{ \sum_{j=0}^k \left[ \rho \cdot C_{j,1} \cdot |P_i - P_{int}|^{n_{j,1}} \left( \frac{P_i - P_{int}}{|P_i - P_{int}|} \right) \right] \right\} = 0 \quad (2)$$

$C_{j,1}$  represents the respective flow coefficient and  $n$  the exponent of each flow path.  $P_i$  describes the outside,  $P_{int}$  the internal pressure of each flow path and  $\rho$  the density of the air. The modeling of the flow paths is briefly explained in the next chapter. Equation 3 describes the modeling of the contaminant concentration (in this case  $\text{CO}_2$ ) of a zone.

$$\begin{aligned} \frac{dc_i}{dt} = & \dot{m}_{inf,i} \cdot (c_a - c_i) + \dot{m}_{vent} \cdot (c_a - c_i) \\ & + \sum_{j=0}^k \dot{m}_{cplg} \cdot (c_j - c) + \dot{m}_c + \dot{m}_{c,i} \end{aligned} \quad (3)$$

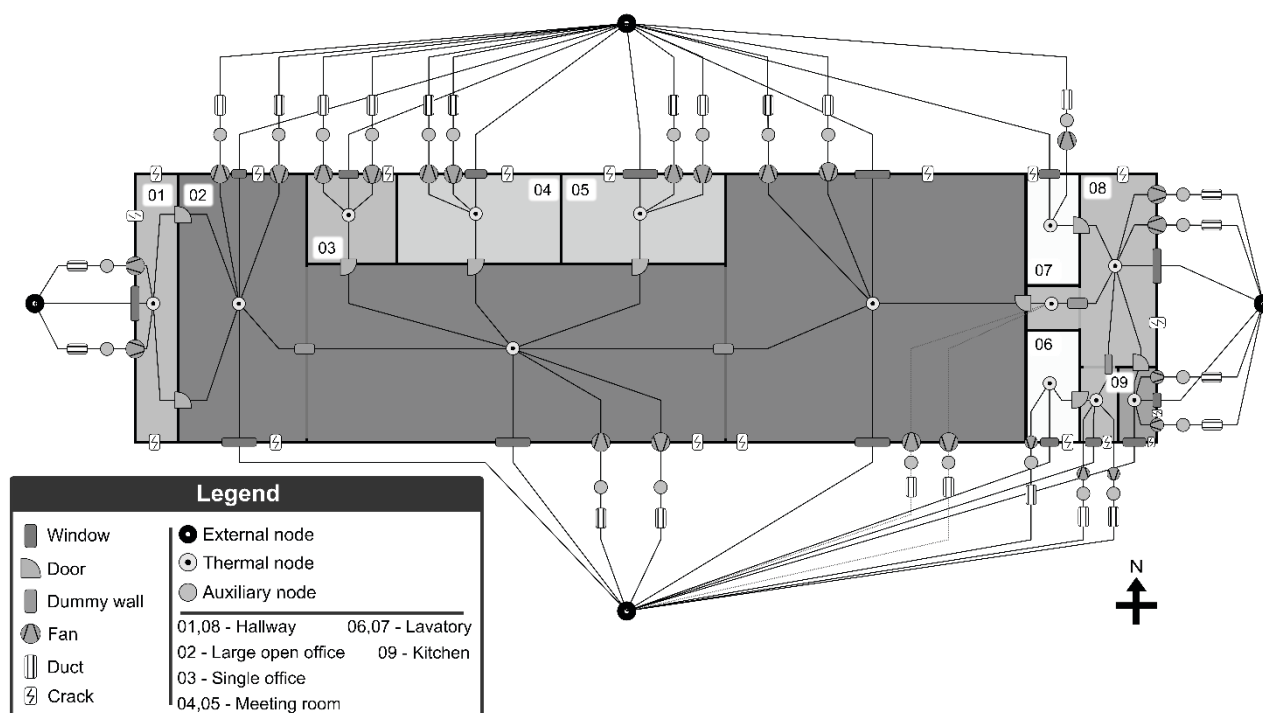
Similarly as in the thermal balance Equation (1), there are components for infiltration  $\dot{m}_{inf,i}$ , ventilation  $\dot{m}_{vent}$  and interzonal airflow  $\dot{m}_{cplg}$ . In each zone, there is an instantaneous contaminant amount of mass  $m_c$  and a source  $\dot{m}_{c,i}$  by persons. The concentrations  $c$  are given by the outside air concentration  $c_a$ , the concentration in the respective zone  $c_i$  and the concentration in the adjacent zone  $c_j$ .

In the following, two simulation models are distinguished, a reference model without airflow simulation and airflow model, which considers the building airflow. The airflow model calculates the infiltration and interzonal airflow depending on the interior and exterior conditions of the building, which then are taken into account in the thermal balance, given by Equation (1). In the reference model, it is assumed that, as in usual building energy simulations applied, no interzonal air exchange occurs between the zones and a standard value of  $n_{int} = 0.1$  1/h is assumed for the air exchange due to infiltration.

### 2.2. General boundary conditions

Within the simulation study, an office building with different user behavior is investigated. In addition to individual and group offices, the building model consists of meeting rooms, sanitary rooms and traffic areas. The building insulation standard is defined according to the requirements of the German Standard EnEV 2016. Building usage, internal heat emission by persons and equipment as well as moisture and pollutant emission are defined in accordance with EN 16798 [8]. The set temperature in zones where people are frequently present (offices, meeting rooms) is assumed to be  $\vartheta_{min} = 20$  °C for heating and  $\vartheta_{max} = 26$  °C for cooling. In zones where people are less frequently present (hallways) and outside opening hours, lower standards regarding the set temperature are assumed, for heating  $\vartheta_{min} = 16$  °C and for cooling  $\vartheta_{max} = 30$  °C. The climatic boundary conditions are assumed for the location Stuttgart, Germany.

The effects of the air infiltration, interzonal airflow and mechanical ventilation in the building are investigated with a complex node and link network (Figure 1).

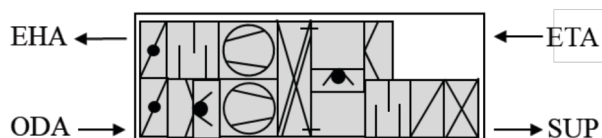


**Fig. 1.** Node and airtight network model

The flow paths of each zone such as infiltration through building envelope, ventilation systems, doors and the interzonal airflow are determined with corresponding correlations for the flow coefficients. These coefficients are determined according to the TRNFLOW manual [9] and the AIVC guide [2], in which also the calculation methods can be found in detail. For the doors inside the building, corresponding opening hours were specified.

### 2.3 HVAC system

The heating, ventilation and air conditioning (HVAC) system is a decentralized air-only system, which controls the inlet air temperature and airflow rate by using a constant PI controller (Figure 2). In heating and cooling case, the system decides whether it is energetically more efficient to use recirculation air or additional outside air to remove the thermal loads of a zone. For example, in case of heating, the fraction of outside air is reduced to a minimum, whereas in case of cooling the outside air can often be used for cooling. The efficiency of the heat recovery is 80 % and is controlled with a bypass for frost protection.



**Fig. 2.** Decentralized HVAC system

In this simulation study, it is assumed that the volume flows supplied by the air conditioning system are equal to those that are exhausted.

### 2.4 Simulation variants

Basically, two influencing parameters are changed. On the one hand, different airtightnesses of the building envelope are investigated, and on the other hand, the ventilation rate of the ventilation system is varied. Three classes are defined based on European and German Standards.

#### 2.4.1 Building's airtightness

According to the standard EN 12831 [10], there are different airtightness categories for buildings. Using the airflow model, different airtightness classes can be investigated and their effects on the energy demand can be analyzed. The airtightness in buildings is usually examined with the so-called indoor blower test. The infiltration volume flow is measured at a pressure difference of 50 Pa between the outside and inside the building. In order to meet the requirements of the German Standard EnEV, an infiltration volume flow of 2.5 m<sup>3</sup>/(h·m<sup>2</sup>) must not be exceeded for non-residential buildings. Therefore According to EN 12831, the airtightness class one must be achieved. Three airtightness classes are considered in this study (Table 1).

**Table 1.** Air leakage per area for each airtightness class

Airtightness	Airflow per area in m <sup>3</sup> /(h·m <sup>2</sup> )
high	2.33
medium	6.0
low	12.6

## 2.4.2 Outdoor ventilation rates

Three classes for the investigation of different ventilation rates are considered. The standard category 2, selected according to EN 15251 [11] to determine the ventilation rate, which leads to a CO<sub>2</sub> concentration in a zone of 500 ppm above the outside air concentration. This represents the medium class and the ordinarily design used in Germany. The standard ventilation rate according to EN 16798 [8] is determined according to category 3. The categories are mainly identical in both standards, but in the newer standard EN 16798, category 3 is defined as the minimum standard for health purposes. According to this standard, a CO<sub>2</sub> concentration of 1350 ppm above the outside air concentration is therefore expected. In the case of high ventilation rate, the German Standard DIN V 18599 [12] was applied. According to this standard, the traffic areas are not ventilated. However, the total ventilation rates are considerably higher than in the other two classes, low and medium. This can be seen in Figure 5, in which the specific outdoor ventilation rates of all three classes in view of different user behavior are presented.

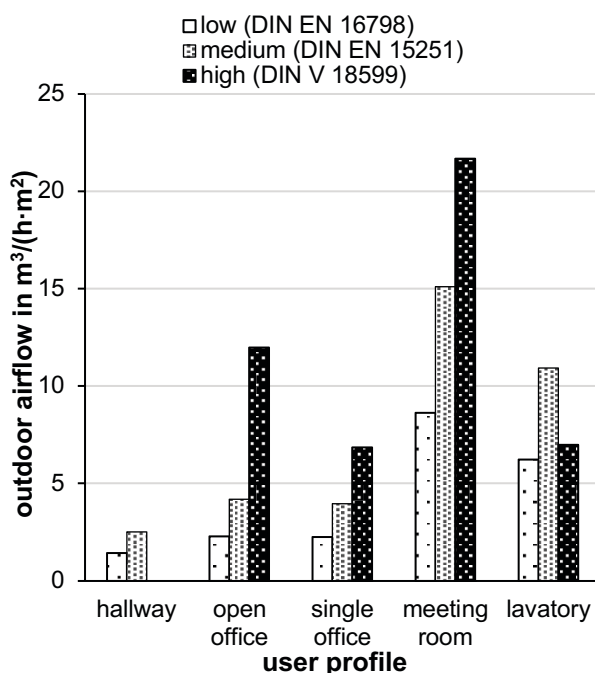


Fig. 3. Specific outdoor airflow rates per area for all three classes

Table 2 lists the total building ventilation rates  $\dot{V}_{OA}$  of the individual standards including the air exchange rate  $n_{tot}$ . The international standard ASHRAE has not been considered. At this point, it is sufficient to know that the ventilation rates specified in ASHRAE are slightly below those of EN 16798 category 3 and are therefore comparable.

Table 2. Total outdoor airflow rate for all classes

Reference	Class	$\dot{V}_{OA}$ in m³/h	$n_{tot}$ in 1/h
DIN EN 16798 (category 3)	low	1675	1.4
DIN EN 15251 (category 2)	medium	3013	2.4
DIN V 18599-10	high	6499	3.0

Furthermore, in Table 3 the assumed number of persons per area of the individual usage areas for all classes is shown, which are calculated according to the corresponding standard.

Table 3. Presence of persons per area for each class

Reference	User profile	m²/pers
<b>low</b> DIN EN 16798 (category 3)	single office	10
	large open office	17
	meeting room	2
	hallway	0
	kitchen	n/a
<b>medium</b> DIN EN 15251 (category 2)	single office	10
	large open office	15
	meeting room	2
	hallway	0
	kitchen	n/a
<b>high</b> DIN V 18599-10	single office	14
	large open office	10
	meeting room	3
	hallway	0
	kitchen	3

In extant literature, the Pettenkofer number is often used to assess indoor air quality. This number takes the CO<sub>2</sub> concentration in the room air as an indication of the room air quality or pollutant load. The historical limit value of Pettenkofer is 1000 ppm. Based on a CO<sub>2</sub> concentration of the ambient air of approximately 400 ppm, the Pettenkofer number is thus classified in a room air category between IDA 2 and IDA 3 according to EN 15251. Therefore, in this study, a limit value of 600 ppm above the ambient air concentration is specified.

## 3 Results

### 3.1 HVAC system performance

The results presented in this subchapter are based on the standard variant, in which a medium ventilation rate and a high building airtightness are assumed. In the following chapters 3.2 and 3.3, the results of the variants described in chapter 2.4 are presented. As mentioned before, the control strategy of the system controls the supply air volume flows according to the thermal requirements in each zone. Figure 4 shows an annual analysis of the supply air volume flow of the entire building,

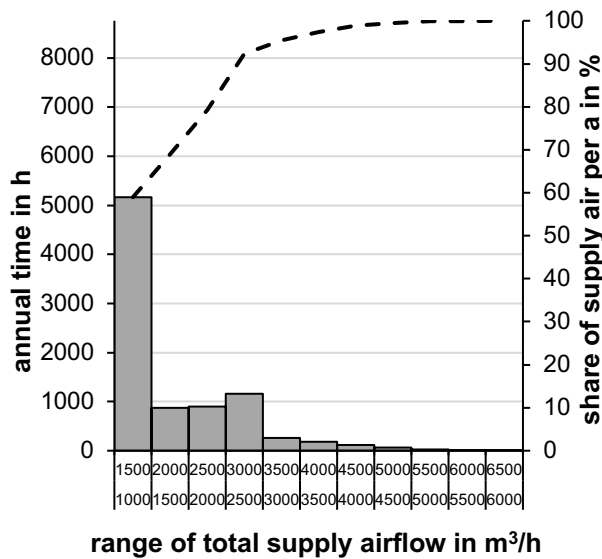


Fig. 4. Total supply airflow of the building

which is required to dissipate the air contaminant and thermal loads of the building. The largest share in the range between 1000 and 1500 m<sup>3</sup>/h represents the share for the basic ventilation rate, which must be guaranteed all day and night in order to reduce the emissions caused by the building material and equipment. The second largest proportion between 2500 and 3000 m<sup>3</sup>/h represents the ventilation rate of the building during the presence of persons. Higher ventilation rates up to 6000 m<sup>3</sup>/h are necessary in case of high thermal load requirements for cooling and heating. Figure 5 shows the distribution of additional outdoor and recirculation air for one exemplary zone (single office), which is required to remove the thermal loads.

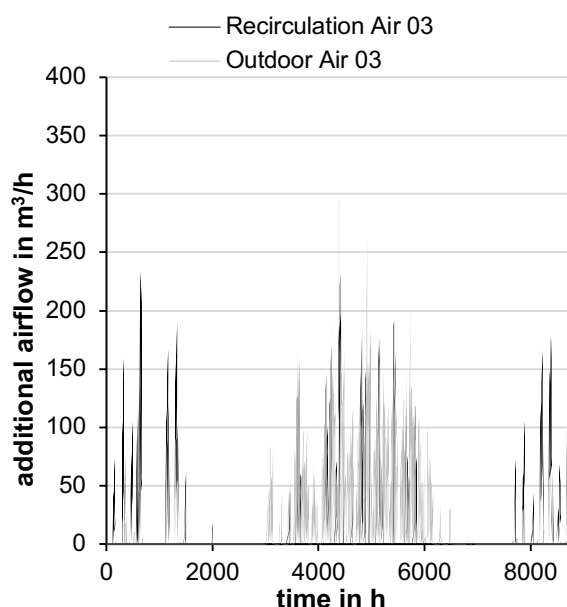


Fig. 5. Annual outdoor and recirculation air of the HVAC system in the single office

It can be seen that additional outdoor air is mostly supplied in the cooling case, whereas recirculation air is usually used in the heating case. This is due to the control algorithm, which compares the temperature after the heat recovery and the room air temperature and, therefore, decides to use additional recirculation or outdoor air to ensure a specified room temperature.

### 3.2 Influence of the building's airtightness

All three airtightness classes are compared with the reference model considering the energy demand for heating and cooling. As expected, the heating energy demand increases significantly (about 40 %) from high to low airtightness of the building envelope and thus increasing in- and exfiltration.

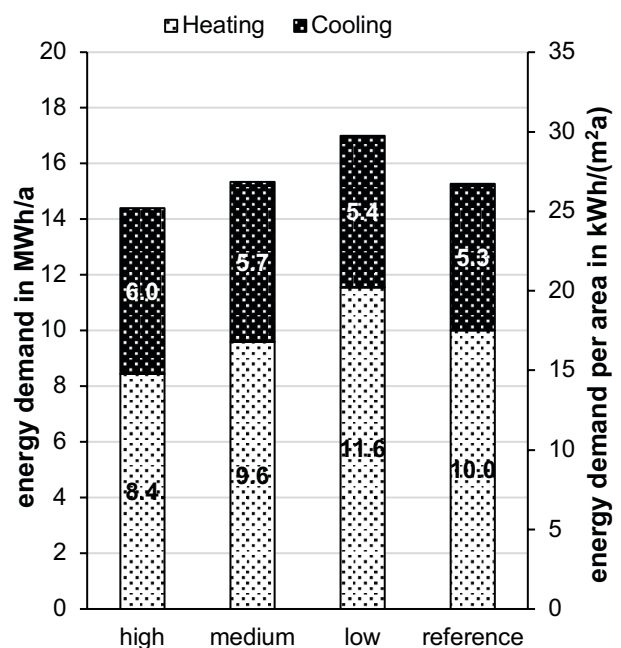


Fig. 6. Total energy demand for cooling and heating for all classes of building's airtightness

It can also be seen that the cooling energy demand is reduced to a lesser extent, but it is not comparable with the increase of the heating energy demand. Therefore the total energy demand increases with the low airtightness by about 18 % compared to the model with high the airtightness. This can be explained by the annual air exchange of the exemplary single office shown in Figure 7. The air exchange calculated by the airflow model is affected by significant fluctuations due to the actual weather conditions. In the case of the low air tightness, the calculated air exchange is at a considerably higher level than in the reference model.



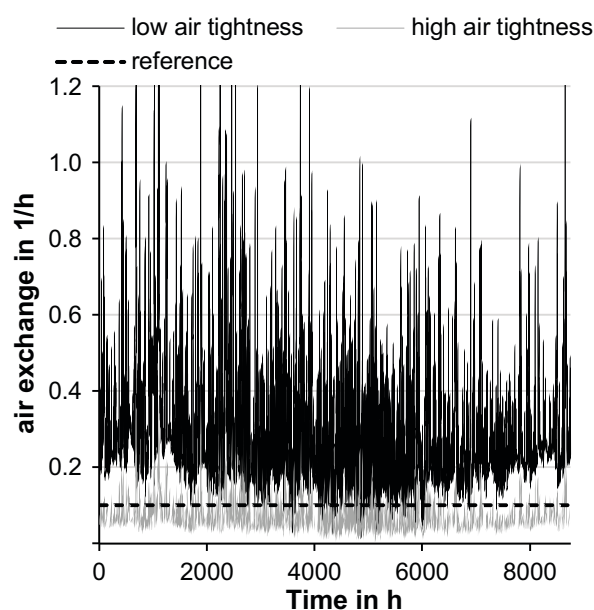


Fig. 7. Annual air exchange of the single office

The air exchange at the medium airtightness is not shown in Figure 7 for a better overview, as this one lies between the air exchange of the low and high building airtightness. It is obvious that the simplified reference model represents a building airtightness between medium and low, but it does not meet the requirements of the German Standard EnEV for non-residential buildings.

### 3.3 Influence of the ventilation rate on the energy demand and air quality

Ventilation rates are a major influencing factor when it comes to energy demand. The results in Figure 8 show that the heating energy demand increases significantly with rising ventilation rates. At the lowest ventilation rate, an almost uniform distribution of the required annual cooling and heating energy can be seen. Due to the increasing fraction of outside air, the heating energy requirement is almost four times higher with the high ventilation rate. The cooling energy demand, on the other hand, is only reduced by approximately 30 %. The ventilation rates not only show a great influence on the energy demand, but also, as is to be expected, on the air quality.

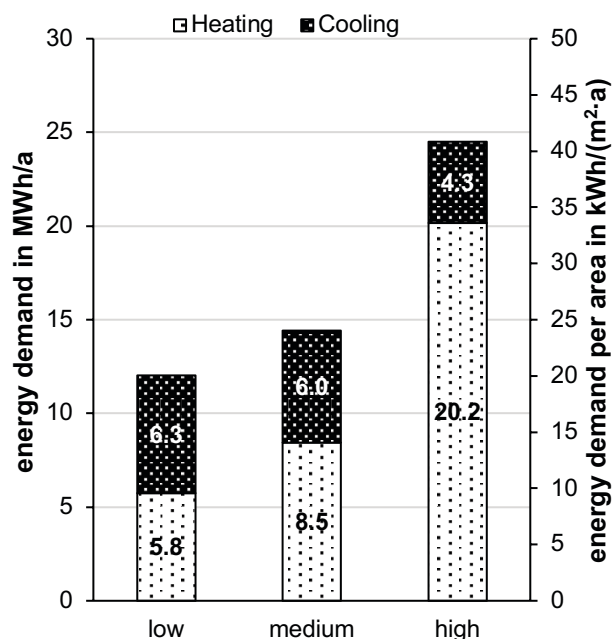


Fig. 8. Energy demand for heating and cooling for all classes of ventilation rates

The CO<sub>2</sub> concentration of the air in ppm above the outdoor air concentration is used as a criterion for assessing indoor air quality. Figure 9 shows the CO<sub>2</sub> concentration over one day in different zones with the low ventilation rate.

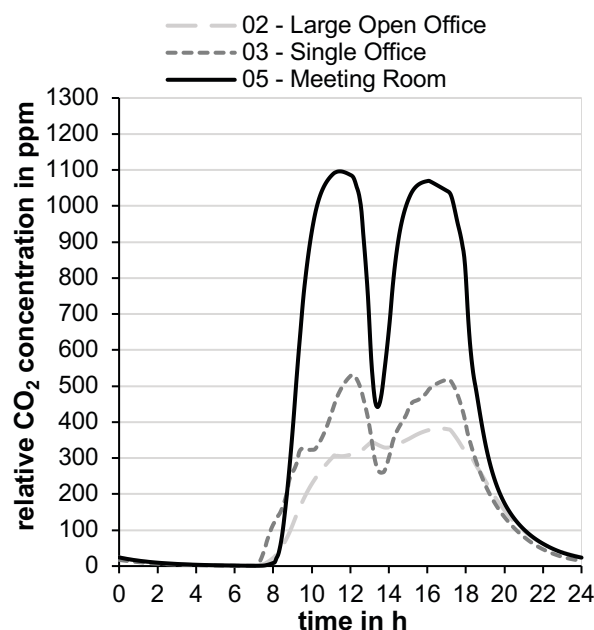
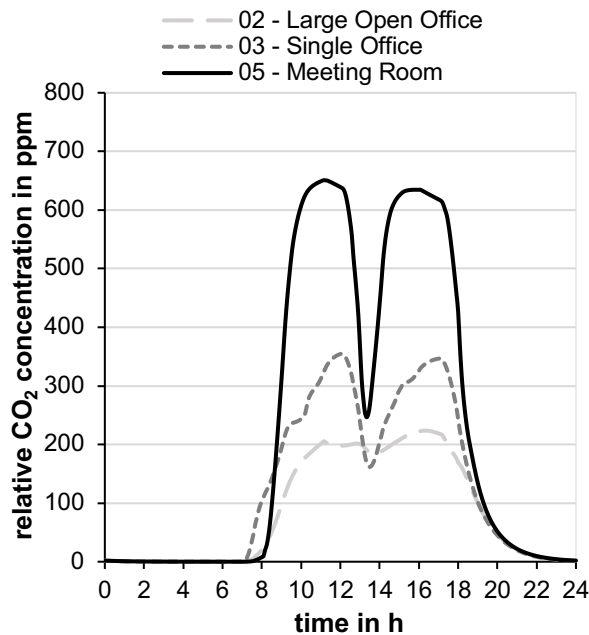


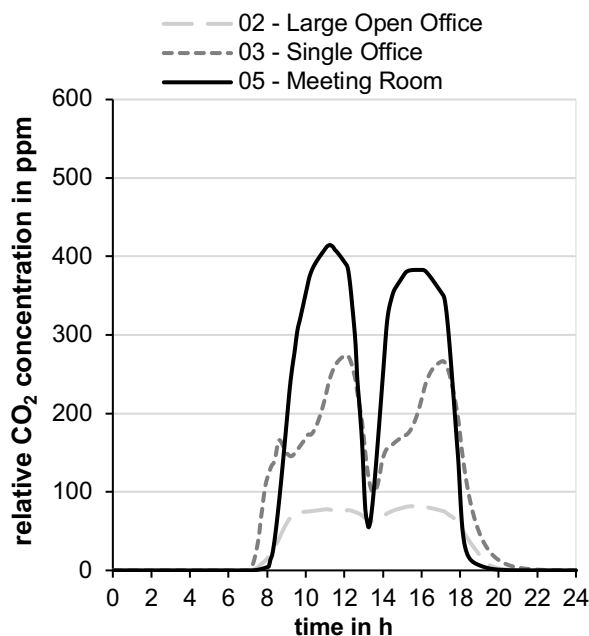
Fig. 9. CO<sub>2</sub> concentration at the low ventilation rate

Due to the relatively low occupancy density in open-plan offices and individual offices, the CO<sub>2</sub> concentration increases to a maximum of 400 or 500 ppm with the low ventilation rate, which from this point of view is sufficient. In the conference room, the high occupancy density with the same ventilation rate leads to a temporary CO<sub>2</sub> concentration of over 1100 ppm and therefore can quickly exceed the limit when all people are present.



**Fig. 10.** CO<sub>2</sub> concentration at the medium ventilation rate

As expected, by increasing the ventilation rate, the CO<sub>2</sub> level decreases continuously in all considered zones in the case of medium (Figure 10) and high (Figure 11) ventilation rate. With the medium ventilation rate, the historical Pettenkofer number (600 ppm) is exceeded in the meeting room only slightly.



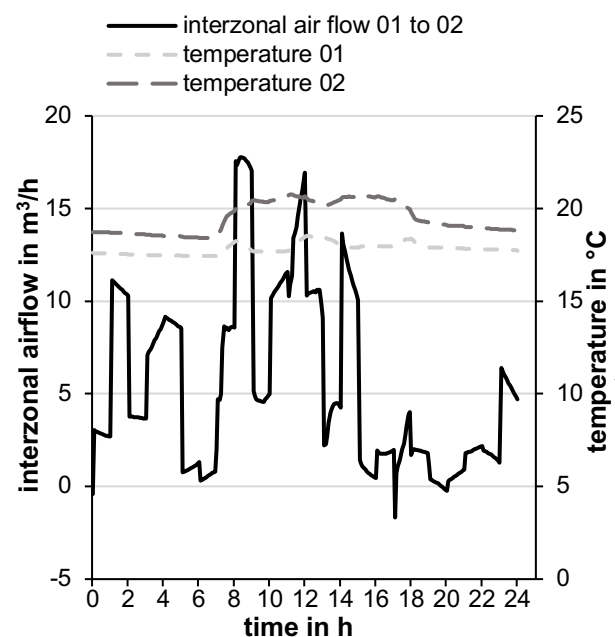
**Fig. 11.** CO<sub>2</sub> concentration at the high ventilation rate

In the case of high ventilation rates, CO<sub>2</sub> concentrations are significantly lower, which corresponds in the meeting room to a 20 % share of dissatisfied persons according to EN 15251 or EN 16798. In an open-plan office, the air quality is almost comparable to that of the outside air. The influence of increased infiltration on the air quality shows

a rather small influence. The airflow inside the building has a more significant influence, i.e., when all doors are open over the whole day, the CO<sub>2</sub> concentration is reduced by 15 % in all zones at the same ventilation rate, as the air qualities of all zones converge due to the increased interzonal airflow.

### 3.4 Interzonal airflow

Interzonal airflow is mainly induced by infiltration and exfiltration volume flows, by open doors and by temperature differences between zones. The ventilation has no influence on the airflow in all zones except the lavatory, as the same supply and exhaust air volume flows are assumed. In the lavatory, only an exhaust air volume flow is assumed, whereby a negative pressure is generated and thus no air can escape. The interzonal airflow through doors is treated as air leakages inside the building, as long as they are closed. When the door is opened, they are treated as large opening, which increases interzonal air exchange. An example of interzonal airflow between the hallway 01 and open plan office 02 is shown in Figure 12.



**Fig. 12.** Interzonal airflow between zone 01 and 02

The airflows in the presented period almost entirely from zone 01 to 02. In zone 01, the set temperature for the HVAC system is 16 °C and, therefore, there is a slight temperature difference. The pressure curve is not shown in the figure. However, the pressure distribution is almost identical to the interzonal airflow and, thus, mostly positive for 01 compared to zone 02. This is mainly due to the smaller infiltration volume flow, as more facade or window area prevails in zone 01.

## 4 Summary and outlook

With the presented simulation method, it is possible to model not only the thermal conditions using an HVAC system but also the building airflow and, therefore, the mass and moisture transport in multizone buildings within annual simulations at low computational effort. Thus, it is possible to investigate different air conditioning systems, control strategies and their influence on the room climate parameters.

The influence of the infiltration shows that the energy demand for heating increases by 40 % from the high building's airtightness to the low one as the high infiltration rate provides ventilation without heat recovery. However, the more significant influence on the heating energy demand is the ventilation rate. This is indicated by an increase of the heating energy demand by a factor of 3.5 in the case of the high ventilation rate compared to the low one. With higher infiltration as well as ventilation, the cooling energy demand decreases, but only to a lower extent so that the total energy demand increases. With higher ventilation rates, also the increased energy demand for the fans' electrical performance inside the HVAC system must be considered, which is not further discussed here.

In the future, further air conditioning systems can be investigated with the presented simulation method. Especially, ventilation concepts, which are designed to provide good air quality in addition to the use of outside air by means of interzonal airflow. This means that the effects of different ventilation concepts, such as centralized and decentralized ventilation systems can be analysed regarding the climate parameter within multizone buildings.

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