COUPLING HYGROTHERMAL WHOLE BUILDING SIMULATION AND AIR-FLOW MODELLING TO DETERMINE STRATEGIES FOR OPTIMIZED NATURAL VENTILATION

Matthias Pazold[*1], Florian Antretter[1], Marcus Hermes[2]

1 Fraunhofer Institute for Building Physics
Fraunhoferstrasse 10
83626 Valley, Germany
**Corresponding author:*
matthias.pazold@ibp.fraunhofer.de

2 Fraunhofer Institute for Building Physics
Nobelstrasse 12
70569 Stuttgart, Germany

ABSTRACT

In both, newly built and renovated buildings the building air-tightness has to be ensured. With a tight building envelope comes a low infiltration air-exchange. A minimum outdoor air exchange to ensure acceptable moisture and indoor air quality levels must be maintained.
A model is introduced, that couples hygrothermal whole building simulation with a multi-zone air-flow simulation. This coupling allows assessing the combined effects of air-flow on building energy use, comfort conditions, air quality and possible hygric issues.
An application example shows the use of the software for a low rise residential building. In a first step the parameterization of the air-flow network is checked by computing the resulting infiltration air-flow with closed windows. The maximum achievable natural air exchange for different window types and openings, like pivot-hung windows, windows opened with a small parallel gap around and side-hung windows is assessed. Based on these numbers it is assessed if any of the above mentioned opening options alone with a certain opening duration is able to achieve good indoor air quality and acceptable indoor moisture levels to avoid any hygric problems or if a combination of some of the measures is required.
The presented dynamic hygrothermal whole building simulation coupled with a multi-zone air-flow model is capable of simulating the effects of different window opening options and strategies on building energy demand, indoor comfort conditions and air quality and on the hygrothermal building component performance. It is shown, that a sufficient air exchange can be realized even with a parallel-action window with small opening gaps which can be run with motor drives. Especially demand controlled opening strategies can be developed that ensure high indoor air quality and comfort conditions while also controlling humidity indoors to avoid moisture damage. Also an improvement for summer conditions can be achieved by ventilative cooling with this type of window opening.

KEYWORDS

hygrothermal building simulation, air-flow-model, WUFI® Plus, natural ventilation

1 INTRODUCTION

The model development bases on a building component tool to simulate the coupled heat and moisture transport across building components, like walls, roofing and floors (Künzel, 1994). It simulates the unsteady temporal development of the heat and moisture profile within a component and, of course the heat and moisture exchange on the component surfaces. Combining simulations for all components of the building envelope and inner walls with a zone model leads to the hygrothermal whole building simulation tool, called WUFI® Plus (Holm, Künzel, & Sedlbauer, 2003). One or different zones describe one or more rooms within the building with equal air properties for each simulation time step. The boundaries of each zone are the building components. Regarding this, the inner and the outer surface of a component are assigned to zones. Besides the heat and moisture transport across the components, solar radiation through windows, inner sources or sinks, HVAC systems and of course the air exchange influence the indoor climate and are taken into account. The indoor climate within zones is calculated with a heat and moisture balance for the whole building model.

An assumed or measured air exchange can be considered as constant, or time scheduled before running the hygrothermal building simulation. But, in fact, the air flow depends on the simulated indoor climate. It also depends on the wind velocity and direction mostly delivered with the outdoor climate data. Therefore a pressure driven multi-zone airflow model (Pazold & Antretter, 2013), quite similar to the model used within CONTAMN (Walton & Dols, 2008), is implemented, to simulate this air flow for each time step. The multi-zone definition of the airflow model is equal to the definition of the zones within the whole building software. If a building component is not fully airtight, is has to be defined as air flow path. Furthermore air openings and fans have to be defined as air flow paths. Therefore different types of sub-models, to calculate the mass flow rate depending on the pressure difference, are used for the different flow patterns. The wind pressure on the outer side of the building envelope and the hydrostatic air pressure are calculated for each path in a respective relative height, to simulate stack effects.

The introduced hygrothermal building simulation tool coupled with the described multi-zone air flow model is used for the investigation of ventilation strategies to determine the optimized natural ventilation for an example low rise building. This paper describes the application of the tool. Different window opening options and strategies are assumed to assess their effect on the indoor comfort conditions, the air quality and the hygrothermal building component performance of the building.

2 LOW RISE RESIDENTIAL BUIDLING MODEL

The visualisation of the investigated two-storey residential building is shown in Figure 1. Each room is regarded as one zone; hence the building exists of 10 heated zones. The attic and the basement excluded the basement stairwell, is regarded unheated. The zone separation enables the assessment of the differing indoor climates within the building because of the inter-zone air flow and among other things, like different inner sources. The treated floor area of the building is 148.51 m² and the net volume (air volume) is 349.3 m³. The characteristic length of the building is 10m and the width 9 m.

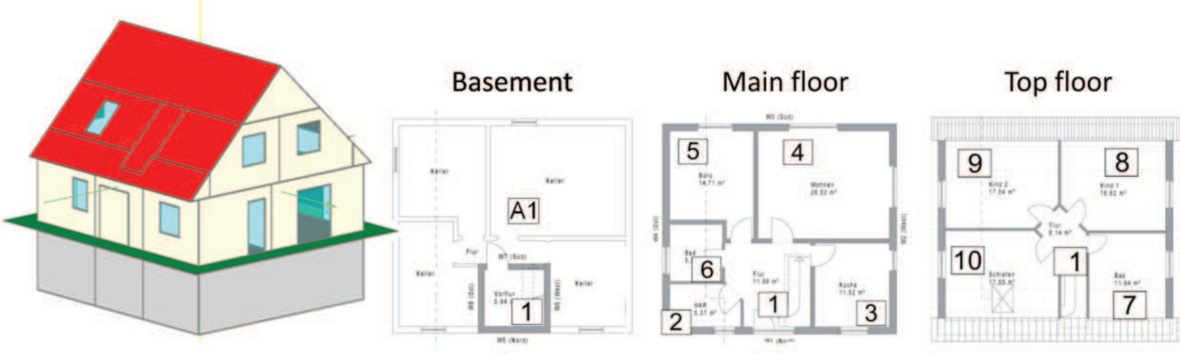

Figure 1: 3-D view and floor plans with zoning of the modelled building

2.1 General simulation assumptions

The location of the building is Holzkirchen in Germany. The used reference outdoor climate data is representative for the temperate climate region. The average outdoor temperature is 6.6°C with a range from -20.1°C up to 32.1°C in summer. The average outdoor relative humidity is 81 %. The average wind velocity is 2.2 m/s mostly from west. An open terrain is assumed to calculate the wind pressure at building height and solar shading.
The investigated simulation period is one year, beginning in January. The result time step is one hour. Built-in moisture effects are taken into account by initializing the envelope components to realistic built-in moisture contents. But 2 months are pre-calculated and not assessed to allow a short dry-out period because of differing boundary conditions after the completion of the building and the following usage. During the investigated simulation period, the building is continuously occupied by four persons, two adults and two kids. Different inner heat-, moisture, and CO_2- daily profiles for each room reflect the day-presence of the residents (Figure 2 and Figure 3). In sum the overall internal heat gain is 11.14 kWh per day; the moisture production is 8.96 kg per day and the CO_2-gain is 3 kg per day for the whole building.

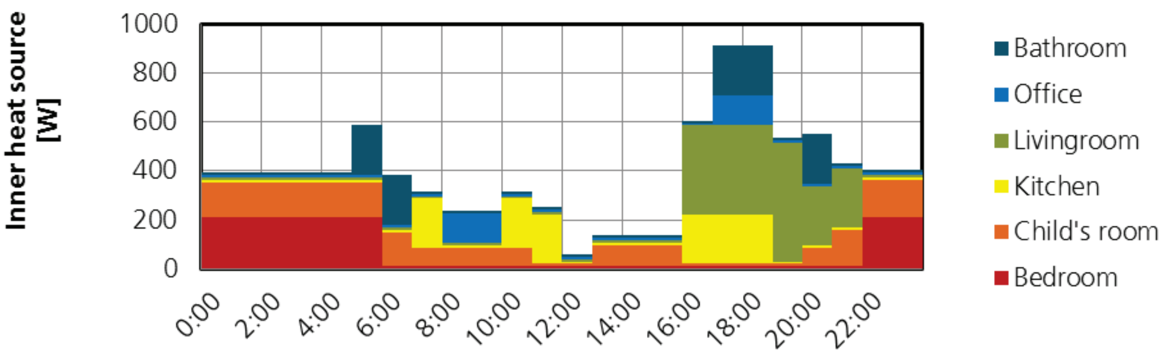

Figure 2: Daily-profile of inner heat gains (summarized for all zones)

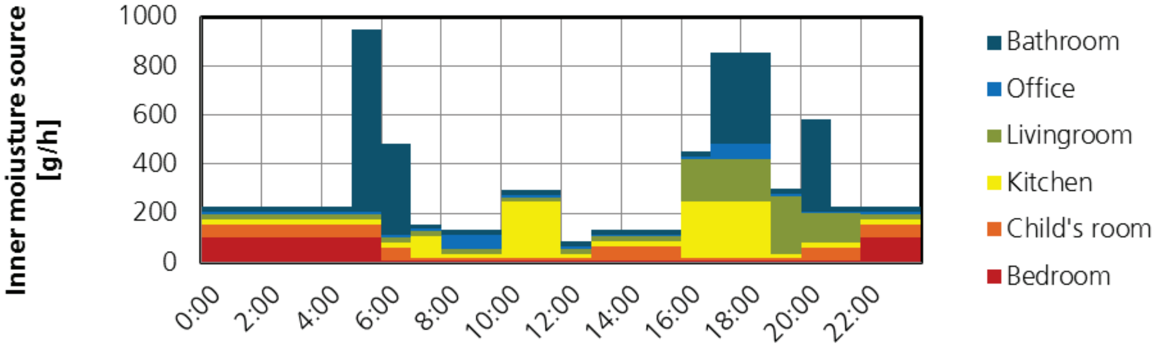

Figure 3: Daily profile of inner moisture sources (summarized for all zones)

An ideal heating system is used to keep the indoor climate at a minimal design temperature of 20°C. If the inner temperature would decrease below this design condition, because of more heat loss than gains within a zone, the actual heating demand is calculated to keep the minimal temperature. The maximal design temperature of 24°C is used for activating the temporary sunscreen device. If the inner temperature would increase above the design condition, the incident solar radiation through the windows is decreased to 10 % due to an activated sunscreen device.

2.2 Building envelope

The simulation tool calculates the coupled heat and moisture transfer through multi-layer building components. Within this paper only a few parameters of the components are presented. The exterior wall is made of aerated concrete with a mineral plaster at the outer side and a gypsum board at the inner side. The resulting thermal resistance is 3.6 m^2K/W. The thermal resistance of the roofing is 5.0 m^2K/W and for the basement slab 2.85 m^2K/W. The U-Value of the windows is 1.3 $W/(m^2K)$ and the solar heat gain coefficient for the transparent area 0.6. Those values meet the current German energy saving ordinance requirements.

2.3 Air flow parameters

The whole building envelope is assumed to be not air-tight. As described in the introduction the air flow across the different components is calculated with the pressure driven multi-zone air flow model for each time step, taking into account the actual inner climate and wind pressure. The mass flow rate through the components is mostly calculated with a power law, fitted for different kinds of flow patterns. The opening state of windows and inner doors can vary during the simulation. The opening times and durations are predefined for different natural ventilation strategies. The model calculating the air flow depends on the opening condition and can change for each time step.
Inner doors can be open or closed. Three states of the windows are investigated. They can be closed or opened in turn-position. As a third position, windows with parallel action fittings are investigated. They can be opened by parallel offsetting the sash by approx. 6 mm to the frame. This creates an air gap on all sides of the casement. With a motor fitting drive the parallel offsetting of the window can be automated, without any user interaction.
The parameters used for each component are given in Table 1. Some are based on (Orme, 1999) Appendix E but adjusted to get a requested air change rate at 50 Pa pressure difference n_{50} = 1.5 h^{-1}. This is checked by a simulated pressure difference test and a whole year simulation with a closed envelope (closed windows and open inner doors). For the difference pressure test, a constant volume flow rate fan is added in the entry door. With an iterative

method, the volume flow rate of the fan is adjusted to reach different pressure differences between the inside and outside air. For the test the wind pressure is neglected and an equal temperature of 20°C, also in the outdoor zone is assumed. With those different pressure differences and their associated volume flow rates, a n_{50}-value of 1.48 h^{-1} is calculated for the closed building air flow network with the defined air flow parameters. This is in good agreement to the requested air permeability, so the chosen air flow parameters seem to be reasonable with this first check.

Table 1: Used air flow parameters

Building Component	Air flow parameters	Related to
Exterior walls	Flow coefficient 0.021 dm³/(s m² Pa^n); Flow exponent 0.84	Wall area
Inner walls	Flow coefficient 0.021 dm³/(s m² Pa^n); Flow exponent 0.84	Wall area
Roofing	Effective leakage area 20cm² on each roof side	Roof sides
Entry door, closed	Flow coefficient 0.12 dm³/(s m Pa^n); Flow exponent 0.6	Joint length
Inner doors, closed	Flow coefficient 1 dm³/(s m Pa^n); Flow exponent 0.6	Joint length
Inner doors, open	Two-way-flow pattern; Discharge coefficient 0.6; Exponent 0.5	Opening area
Windows, closed	Flow coefficient 0.12 dm³/(s m Pa^n); Flow exponent 0.6	Joint length
Windows, open	Two-way-flow pattern; Discharge coefficient 0.6; Exponent 0.5	Opening area
Windows, parallel open	Two-openings; Opening Areas 0.058m² (at the top and bottom of the window); Discharge coefficient 0.162; Flow exponent 0.5	Opening area

3 NATURAL VENTILATION STRATEGIES AND RESULTS

Different natural ventilation strategies are analysed by designing cases with different opening times and states for the windows. Beside the inner air temperature, relative humidity and CO_2-concentration, the air change rate with the outside climate and the inter-zonal air change rates are calculated for each time step and every defined zone. The huge amount of results is evaluated for each case and some average annual values are presented in this paper. Some additional assessments available with the coupled hygrothermal building simulation with the air flow model are shown.

3.1 Closed envelope

In a first step, the natural infiltration due to air leakage was investigated. The windows are kept close for the whole simulation time. In fact, this is not a realistic case, but should also prove the designed air flow network with the air flow parameters. As a result, the average annual natural air change rate for this case is 0.11 h^{-1}. This value can be expected for the requested air permeably of n_{50} = 1.5 h^{-1} and the used outer climate. In 25 % of the year, the air change rate is below 0.04 h^{-1}. The room with the lowest outside air change rate is the upstairs bedroom facing north-east with an average annual value of 0.01 h^{-1}. The inter-zonal air change rate for this room is on average 0.2 h^{-1}. The most outside air ventilated room is the kitchen, (0.26 h^{-1}) facing north-west. The heating demand due to air leakage and without any other ventilation is 51 kWh/(m² year).

3.2 Normal window turn-opening

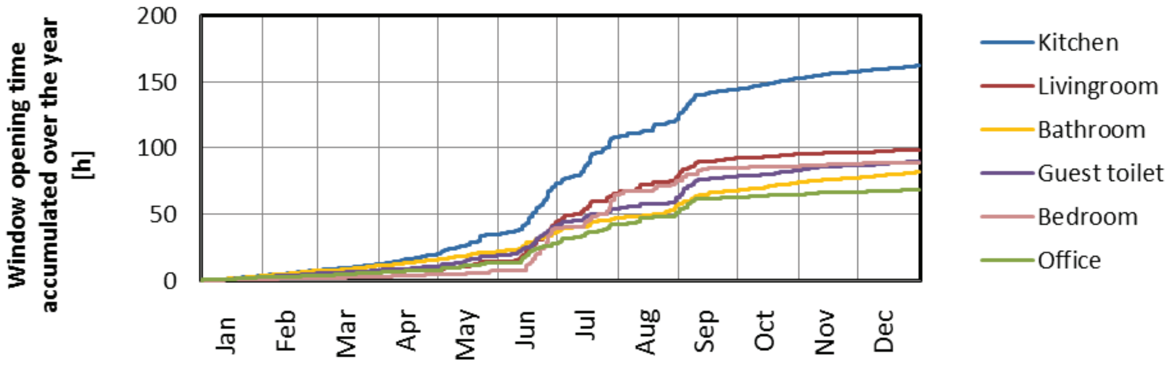

Figure 4: Accumulated window opening time over the simulation year for normal window turn-opening

This case should represent normal user ventilation behaviour by turn-open the windows. The opening times are pre-defined by calculating possible opening durations for each simulated time step depending on climate conditions and user presence. If the possible opening duration is more than zero, the actual opening is randomly calculated with a probability of 20 %.
Only when there is a very low rain load (below 0.1 liter/(m² h)), or when a person is presence in a room the possible opening duration for each window is calculated. Further, if the outdoor temperature in is above 20°C (for the window in the bedroom above 15°C) the window can be opened for the whole time step, one hour. Is the outdoor temperature below this boundary, a short opening for 10 minutes (0 – 20°C) or 5 minutes (below 0°C) can only happen, when a person enters or before leaving a room. With this algorithm, the window in the kitchen is averagely opened twice a day and the windows in the other rooms averagely once a day. In the heating period, the opening duration is 5 to 10 minutes. In the summer a window can stand open for one or more hours. The accumulated window opening times for each window in the different rooms are shown in Figure 4.
The resulting outer air and inter-zonal air change rate for each zone is shown on Figure 5. The resulting average annual air change rate for the whole building is 0.31 h^{-1}, the moving average is shown in Figure 6.
As indicator for the air quality the CO_2-concentration within the rooms is used. For this case the average concentration in the whole building is 44 % of the year above 1500 ppm. Within the worst room, a child's room, it is 73 % of the year above 1500 ppm. Following this the air quality is rather poor. As indicator for the comfort condition the inner air temperature is used. It is 4.3 % of the year above 26°C. The heating demand in this case is 59 kWh/(m² year).
As a first indicator for the hygric issues the relative humidity within the rooms is used. In the winter months the average relative humidity is about 50 %. However, especially in the bathroom, with short high moisture loads, the relative humidity is more than half of the year above 60 % and even one third of the year above 70 % up to 99 %. So the first assumption is that there will be hygric issues at least within the bathroom. Further investigations in order to assess the risk of mould growth under transient conditions can be made with a bio-hygrothermal method. For this investigation, the tool WUFI Bio (the basics are discussed in (Sedlbauer, 2001)), is used to predict mould growth on the interior surfaces. It calculates the moisture content available for mould and compares it with a critical water content which allows a spore to germinate. On the inner surface on the exterior wall of the bathroom, for the substrate category II (materials with porous structure such as the gypsum board) the predicted mould growth rate is 4.6 mm/year and the mould growth index is about 0.008, which seems to

be no issue. However, the simulation is made with an interior thermal resistance of 0.13 (m²K)/W which might have to be increased due to less convection in corners or behind cupboards. Then the surface temperature and the risk of mould growth would increase.

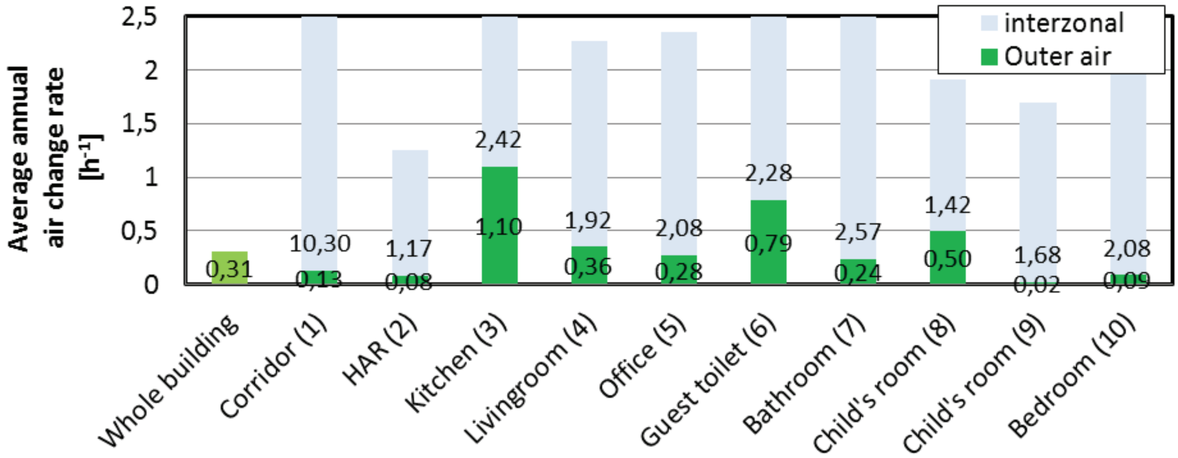

Figure 5: Resulting average annual outer air and inter-zonal air change rates for the different rooms. Results for normal window turn-opening

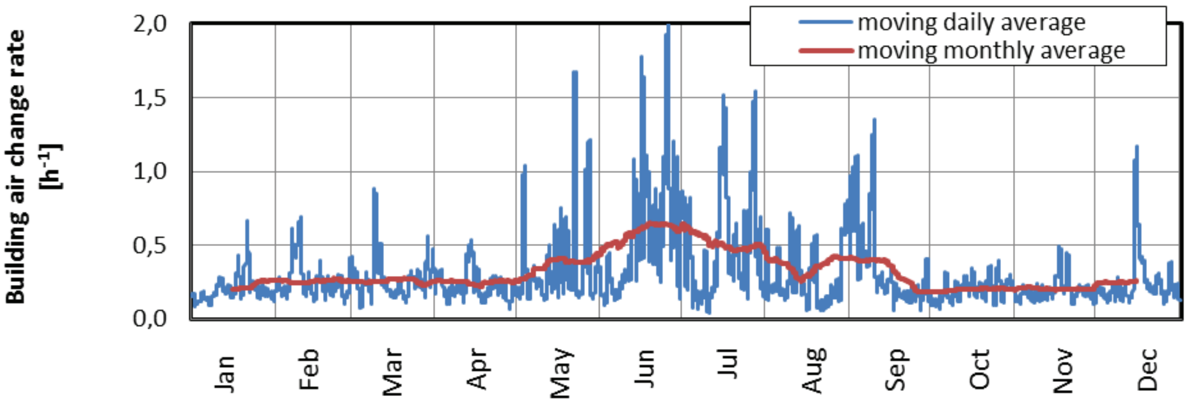

Figure 6: Moving daily and monthly average air change rate within the whole building. Results for normal window turn-opening

3.3 Frequent window turn-opening

This case should represent a frequently user ventilation behaviour by turn-open the windows up to four times a day for 5 till 60 minutes in summer, shown in Figure 7. The algorithm to calculate the opening durations, depending on climate conditions and person presence is equal to the case before with the assumed normal user behaviour. However, the probability calculating the actual opening randomly is set to 50 %.

The average annual air change rate within the whole building is 0.69 h^{-1} for this case. The moving monthly average is mostly above 0.5 h^{-1} and increase in summer up to1.0 h^{-1}. In the kitchen, where the window is west-faced and most frequent turn-opened, the average annual outside air change is 2.5 h^{-1}. The higher infiltration rate increase the calculated heat demand to 84 kWh/(m² year) but the CO_2-concentration is only for 12 % of the year above 1500 ppm and mostly below 2000 ppm. Only in the sleeping rooms, with the high continuous CO_2-source during night time, the CO_2-concentration is about 30 % of the year above 1500 ppm. The average inner air temperature used for assessing the comfort condition is only for a short time during summer, when the outer temperature is quite high, above 26°C, for 2.4 % of the year. The average relative humidity is decreased to 36 % during the winter months and in the bathroom for quite a few hours above 70 %. The bio-hygrothermal model predicts no mould growth on the inner surfaces, the moisture content available for spores is significantly below the critical water content for spore germination.

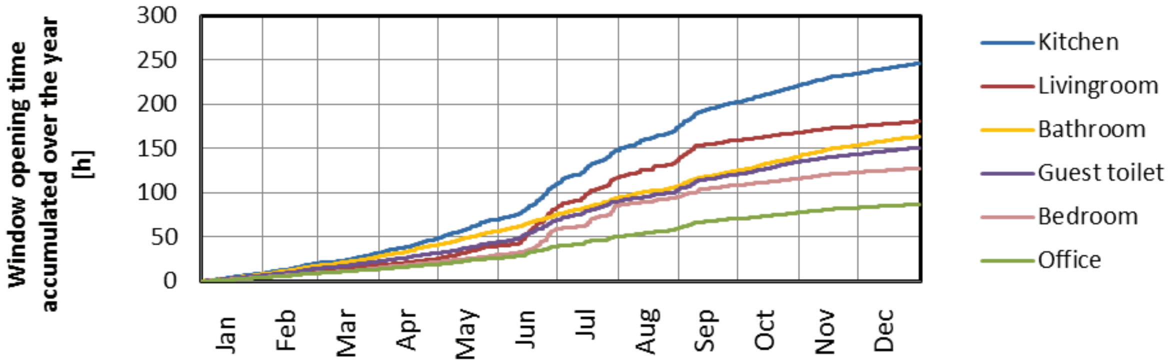

Figure 7: Accumulated window opening time over the simulation year for frequent window turn-opening

3.4 Automatic parallel action window

This presented natural ventilation strategy uses the described automated parallel offsetting of the windows with a parallel action fitting. This ventilation method should require no further occupant interaction to get a good air quality, good comfort conditions, no risk for mould growth and a low heating demand. This shall be checked with this simulation case. The parallel offset of the windows is set to last four hours a day nearby high moisture and CO_2 contribution in the rooms. It is assumed that they automatically open from 5:30 to 7:30, 12:30 to 13:00 and from 18:30 to 20:00. During summer time, when there is no heating demand and the outer air is useful for night cooling, the parallel offsetting of the windows should automatically last longer, even the whole night. For this case the user behaviour is not neglected. It is additionally assumed that the occupants turn-open the windows at least every 4^{th} day for 5 to 10 minutes.

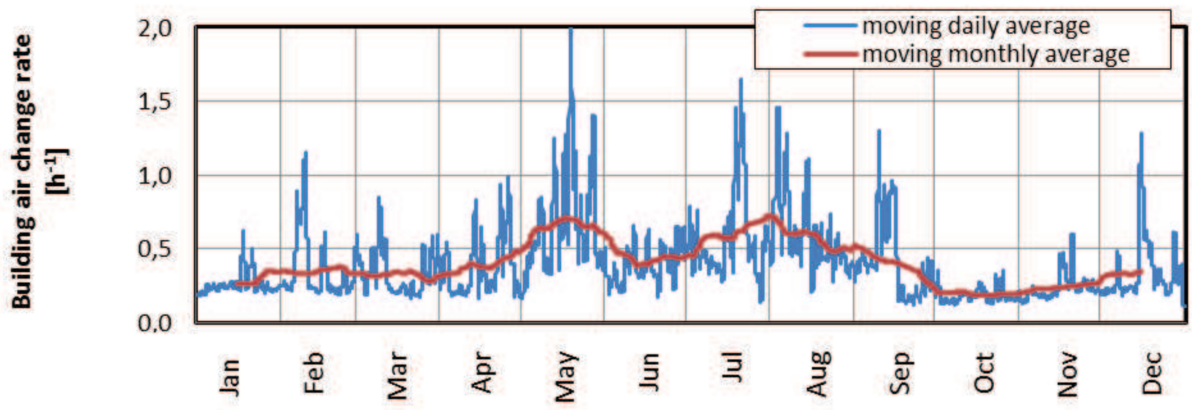

Figure 8: Moving daily and monthly average air change rate within the whole building.
Results for Automated window opening by parallel offsetting the casement

The resulting average annual air change rate is 0.4 h^{-1}, with the moving daily and monthly averages shown in Figure 8. The calculated heating demand, to keep the inner air temperature above 20°C is 67.5 kWh/(m² year). Even with this lower air change rate, and lower heating demand, compared to the case before, the CO_2-concentration within the rooms is on average only 7 % of the year above 1500 ppm and in the sleeping rooms only for 15 % of the year. The inner air temperature is 3.8 % of the year above 26°C. The relative humidity during winter is averaged for the whole building 44 % and in the bathroom lower than in the cases before. The bio-hygrothermal model predicts no mould growth on the inner surfaces.

4 CONCLUSIONS

At first, the coupled hygrothermal whole building simulation with a multi-zone air flow model is introduced. In the following parts of this paper the application of this coupled simulation method is shown exemplary for a low rise building. It is used to determine natural ventilation strategies to optimize the air quality and the comfort conditions by minimizing the heating demand and the risk of mould growth. Only the opening times and durations of the windows are investigated in three presented cases. The first case assumes a normal window opening occupant behaviour. For the second case the turn-opening durations of the windows are more frequent. In fact, for longer turn-opening times, the air quality getting better and the risk of mould growth is decreased, but also the heating demand is increased about 40 %, for the well-insulated building. Both named cases require user interaction. This is not necessary in the last case where the windows should be opened automatically by parallel offsetting the sash to get a 6 mm air gap around the casement. The parallel offsetting of the windows for at least four hours a day show better indoor conditions by less heating demand (14 % more compared to the first case) due to the lower but more continuous air change rates. Of course, there is a lot of input data and results not presented in this paper, but at least some of the results that can be expected by the application of such a coupled whole building simulation tool are presented. Hygrothermal whole building simulation coupled with an airflow model enables a holistic air-flow, air-quality, comfort and energy assessment while also being able to determine possible hygric issues on and in the building components.

5 ACKNOWLEDGEMENTS

This study, especially the coupling of the hygrothermal building software with the air flow model was funded by the German Federal Ministry of Economics and Technology (BMWi 0329663L). The application cases, especially the last with the parallel action fitting windows originated in a project called “Natürliche Lüftung” realised with D+H Mechatronic AG, Hella Automation GmbH, H.O. Schlüter GmbH und Aug. Winkhaus GmbH & Co. KG.

6 REFERENCES

Holm, A., Künzel, H. M., & Sedlbauer, K. (2003). The hygrothermal behaviour of rooms : combining thermal building simulation and hygrothermal envelope calculation. *Proceedings of the 8th International IBPSA Conference.* Eindhoven, Netherlands.

Künzel, H. M. (1994). Simultaneous Heat and Moisture Transport in Building Components. *Dissertation*. University of Stuttgart.

Orme, M. (1999). TN 51: Applicable Models for Air Infiltration and Ventilation Calculations. AIVC Technical Note 51.

Pazold, M., & Antretter, F. (2013). Hygrothermische Gebäudesimulation mit Multizonen-Gebäudedurchströmungsmodell. *Bauphysik, 35.*(2), pp. 86-92.

Sedlbauer, K. (2001). Prediction of mould fungus formation on the surface of and inside building components. *Dissertation*. University of Stuttgart.

Walton, G. N., & Dols, W. S. (2008). CONTAM 2.4c User Guide and Program Documentation. NISTIR 7251, National Institute of Standards and Technologiy.