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Investigating Night Flushing Potential in a Multi-Storey, Open-Plan Office in Germany Using TRNLizard with TRNSYS 18

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Abstract. Despite growing interest in sustainable office buildings and technological advancements, often either comfort or energy is sacrificed at the expense of the other in the conventional approach. This paper argues that wellness and energy savings are not contradictory aspects of design. An integrated design concept needs special considerations at the early stages using an accurate and fast simulation tool that considers dynamic thermal, daylight and airflow models. However, some passive measures such as natural ventilation are more difficult to simulate and validate due to the complex, non-linear relationship between wind forces and thermal buoyancy. The aim of this paper is to demonstrate the use of TRNLizard, an integrated thermal, daylight and airflow simulation tool based on Rhinoceros 5, Grasshopper, TRNSYS18, DaySIM and TRNFlow to develop and validate the concept for an energy efficient office building with a healthy, comfortable environment. The office building is located in Germany with a highly glazed façade and night ventilation for passive cooling. It is shown that night flushing reduces annual end-use cooling energy and peak cooling load of mechanical air conditioning systems by 55% and 15%, respectively.

Introduction

Office Buildings. Several empirical and theoretical studies have demonstrated the importance of daylight and fresh air supply in office buildings because of their relation with comfort, wellness and energy loss [1–5]. The oil crisis in 1973 compelled a global shift towards new national energy regulations that focused on energy conservation, while neglecting its impact on occupant health and wellness [1]. Many of the newly constructed offices in the 1980s suffered from the sick building syndrome and other building-related illnesses [6]. The 1990s saw a shift in attitude towards a better quality of the indoor environment [1]. This change combined with technological developments in curtain wall façades led to modern office design's shift towards fully-glazed façades, highly insulated and airtight building envelopes, open floor layout, and dense workplace. This shift caused higher cooling and mechanical ventilation demand to satisfy the flexibility required in the workplace environment; at the same time, access to daylight and visual connection to the outside considerably improved occupant wellness, and thus, productivity in an office environment [1,7–8].

In a typical, highly insulated, administrative building in temperate climates such as Germany, a significant portion of the primary energy demand is due to cooling, mechanical ventilation and lighting [9]. As such, this paper focuses on the influence of passive measures regarding cooling, ventilation and lighting to create a comfortable office space with a positive environmental impact.

Often natural ventilation is disregarded on the grounds that it is a source of discomfort, not providing energy benefits, or difficult to accurately model in early stage design, in particular, for a building with an open space layout and open interior atriums [10, 11]. The key is to develop an integrated natural ventilation concept for an office space with great daylight quality, sufficient connection to the outside and a low energy consumption without compromising occupants comfort.

Passive Design Simulation Challenges. Modelling the impact of natural ventilation and daylight on heating, cooling, ventilation and lighting energy as well as user comfort requires an integrated simulation tool that is accurate enough to yield meaningful information that helps with important design decisions in an early design phase. The challenge is that such a tool needs to be based on thermodynamics, aerodynamics and radiation principles; yet, it is desired for the design tool to offer simplicity of interface, ease of parametric studies and convenient and fast methods of setting up complex geometry. For example, although the effectiveness of passive cooling via night ventilation has been established in several studies as well as many built examples throughout the world [12–15], there is a lack of design tools for early stage decisions that significantly affect passive design. First decisions are the most important for passive design measures, such as orientation, atrium design, programming of spaces, opening areas, control strategies and so on.

The natural ventilation process in a building is driven by the wind pressure on building's façades and the temperature difference between inside and outside, known as the stack effect. What makes passive cooling potential difficult to model at an early design stage is the complex behavior of airflow in an open-office building with open atrium due to the non-linear interaction between wind forces and stack effect. Additionally, a multi-zone model with non-uniform internal temperatures is required to more accurately model the behavior of air circulation throughout the different spaces.

The aim of this paper is to demonstrate the use of the interface TRNLizard for Grasshopper in Rhinoceros 5.0, an integrated thermal, daylight and airflow simulation tool in order to provide the basis for general strategy, refinement and validation of the concept for a low energy office building. The concept focuses on a hybrid ventilation concept that maximizes the comfort during occupancy in daytime and allows the use of night flushing for passive cooling purposes.

Methodology

Case Study. The case study is in Regensburg, Germany. The local climate is characterized as temperate, humid continental. It is worth noting that the case study does not include variants that influence winter comfort, and subsequently the heating demand; a building with a high-performance envelope is selected to ensure an exceptional comfort in winter with a low heating demand.

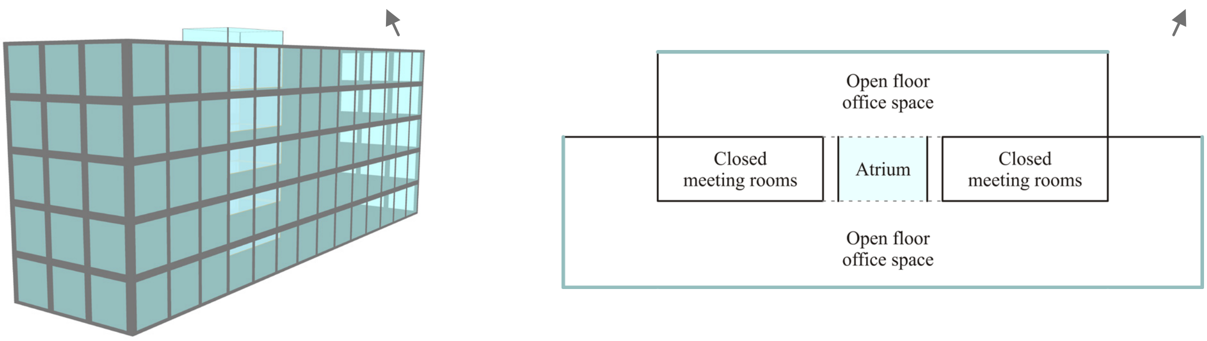

Fig. 1. Case study: A 5-storey office building in Germany with open floor office and a central atrium

A 5-storey office building with a central atrium, Fig. 1, is modelled to evaluate the impact of night ventilation. The 3900 m² building contains open plan offices and a few closed meeting rooms.

Passive Design. The external façade of about 75% glazing provides great daylight and connection to the outside, improving health, motivation and productivity. The high performance double glazing, with u-value 1.07 W/m²K and SHGC 0.63, reduces heat losses in winter. External shading is utilized to protect from overheating in summer or glare.

The advantage of a central atrium is facilitating natural ventilation to reduce sizing of mechanical ventilation and cooling systems while providing fresh air and comfortable temperature ranges. The central atrium extends above the building roof with a 1.5 meter-fully glazed space and integrated exhaust openings. The negative pressure on top of the atrium combined with mixing of air in the atrium drive the flow of air from the office. The east and west offices are linked to the south office, and the north and south offices are directly linked to the atrium via vertical openings.

The conventional arguments against using an atrium exhaust and natural ventilation in an open office are the following: i) the exhaust through the atrium does not work very well in the absence of wind; ii) the mid-level floors (where the neutral pressure plane occurs depending on the pressure profile) do not benefit from the airflow due to lack of pressure difference; iii) the exhaust through the atrium might cause backflow of warmer, recirculated air.

Using an integrated thermal, daylight and airflow simulation addresses the abovementioned concerns, validates the concept of a central atrium combined with night ventilation, and demonstrates the potential for energy consumption reduction. The evaluation criteria are: daylight quality, total energy consumption and occupant thermal comfort.

TRNLizard Components. TRNLizard is a component library for the 3-D modelling software Rhinoceros 5 and its graphical algorithm editor, Grasshopper. It enables dynamic thermal and daylight simulation with TRNSYS 18 using a variety of artificial lighting, mechanical and natural ventilation, heating and cooling concepts based on detailed, multi-zone 3D building geometry.

TRNLizard with TRNSYS 18 offers the option to calculate artificial lighting with daylight control using results based on DaySIM. DaySIM is a validated, radiance-based daylighting analysis software that models the annual amount of daylight in and around buildings [16].

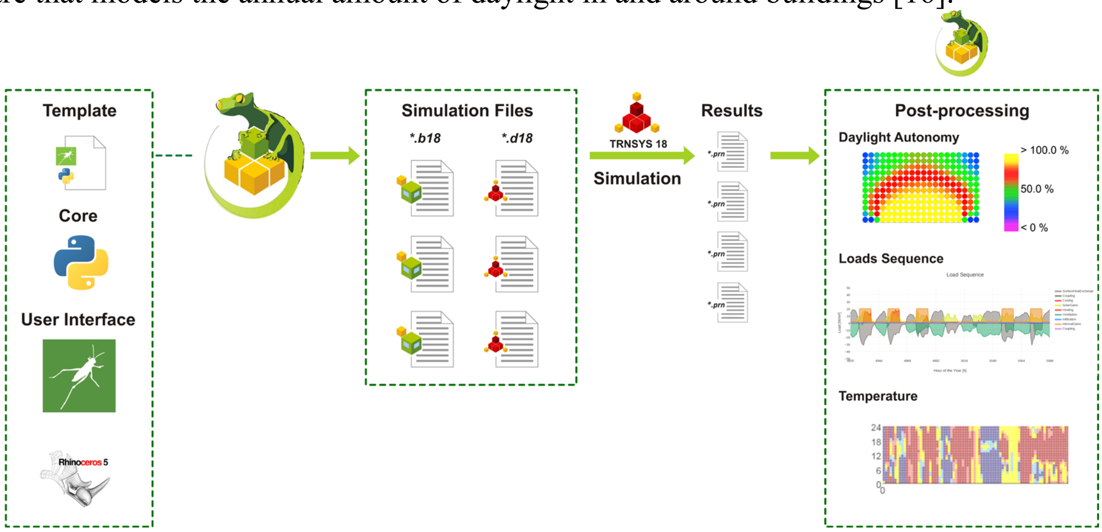

Fig. 2. TRNLizard workflow

A prototype of TRNLizard connects to TRNFlow to simulate air flow concurrently with daylight and thermal simulations. The TRNFlow plug-in addition to TRNSYS allows for both heat and mass transfer between zones based on the COMIS multizone airflow calculation model. It accounts for the wind pressure on each façade and the indoor and outdoor air temperature difference, with the indoor air temperature taken from the dynamic thermal simulation [17].

To account for the non-uniform internal temperatures, the building is set up as a multi-zone geometry, with the airnodes' temperature in each zone used for airflow calculations in between the different interior zones. The building is then modelled as a network of nodes and air flow links between them. The *nodes* represent office spaces, atrium, and building surroundings. The *links* depict openings, doors, window joints as well as ventilation components like atrium, Fig. 3. The horizontal surfaces are modelled as a two-layer exchange flow to allow for upward and downward flows in the atrium. The vertical openings between the outside, the office spaces and the atrium are modelled as vertical large openings, which accounts for two-directional flow by height differences.

To properly model the wind effect at different heights and orientations, the pressure coefficient, Cp-values, are calculated using CpCALC+ developed by Grosso Mario. The CpCALC+ tool calculates Cp-values for given conditions of wind direction, shape ratios, terrain roughness and density of surrounding buildings [18]. In addition to the pressure coefficient, a discharge coefficient (Cd-value) is applied for each large opening in order to take into account the physical effects of flow contraction and friction loss [17]. The Cd-value is automatically calculated by TRNFlow as described in its manual at each simulation time step [17]. For external openings, the calculated Cd-values depend on the room depth (distance from the opening to the opposite wall) and the wind speed, while for openings between airnodes, the Cd-values depend on the ratio of the room height to the door height [17, 19].

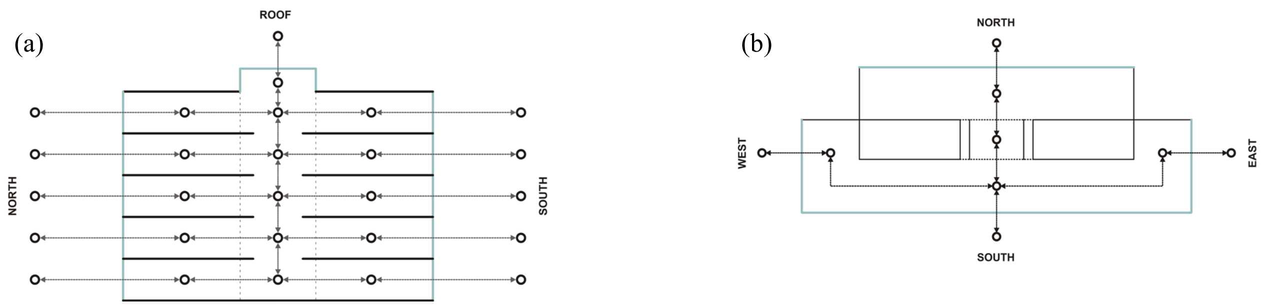

Fig. 3. TRNFlow links and nodes for simulating airflow from the outside through the office spaces into the atrium and exhaust through the atrium; (a) section, (b) plan

Simulation Inputs and Assumptions. Typical weather data is used from the Test Reference Year (TRY2010) for Mühldorf, the reference weather station for the project location, as provided by the Deutscher Wetterdienst. The indoor conditions are maintained according to the adaptive comfort criteria outlined in DIN EN 15251-NA, National Appendix Category II [20] for the occupant schedule and internal heat gains depicted in Table 1. The night ventilation is in operation during the intermediate and hot seasons defined under the conditioned tabulated in Table 1. The geometrical opening area in the façade is about 0.44% per m² of the floor area. The meeting rooms are enclosed but all other inner spaces, in between zones and the atrium, are fully open.

Table 1. Simulation Boundary Conditions

Occupant density	10	m²/person	
Occupancy schedule	8 AM – 7 PM		
Internal heat gains:			
During occupancy: Person	75	W/person	*sensible heating for seated person [20]
During occupancy: Equipment	70	W/device	*for density of 10 m²/device
During occupancy: Light	10	W/m²	*with daylight control
All day: Miscellaneous equipment	1.5	W/m²	
Night flushing allowed if:			
Mean daily ambient temperature	Above 9	°C	
And indoor air temperature	Above 21.5	°C	
No night flushing if:			
Ambient air temperature	Above 26	°C	
Or indoor air temperature	Below 18	°C	
Ventilation rate:			
Mechanical ventilation (occupancy)	39	m³/h per person	
Nocturnal ventilation (no occupancy)	Up to 5	ACH	*only allowed at night from 7 PM – 8 AM

Variants. Wind-induced ventilation of buildings is greatly influenced by the surrounding buildings. Therefore, it is interesting to explore whether night ventilation works when there is no wind, either on a clear night or due to wind speed reduced by the surrounding urban block.

To investigate the impact of night ventilation, the following three cases are simulated: i) fully mechanically ventilated and conditioned as the base reference case, ii) naturally ventilated at night, when there is no occupancy; the impact of wind-driven ventilation is ignored, iii) naturally ventilated at night with wind included. All variants have the same envelope definition, boundary conditions and the same meteorological conditions, as described previously; with the ventilation mode and wind forces as the only variants, to allow for meaningful comparisons. As such, heating demand and daylight quality are almost the same in all cases.

Results and Discussion

Evaluation Focus 1: Space Quality. Fig. 4 demonstrates the daylight autonomy for various spaces. Fig. 4a shows the daylight autonomy on the north office spaces, as the orientation with the lowest access to daylight. Fig. 4b and Fig. 4c depict the whole floor plan on the first and top floor, the worst and best levels for daylight. All spaces meet the German Sustainable Building Council (DGNB) recommendation for access to daylight with daylight autonomy above 75%.

A conventional office building that is fully sealed with no natural ventilation or central atrium, requires a significantly reduced window-to-wall ratio to reach the same amount of energy savings as the building proposed in this paper. In other words, the conventional approach would compromise daylight and space quality to guarantee energy savings. Additionally, the low energy, fully glazed office building proposed in this paper does not cause summer overheating; thermal comfort per DIN EN 15251 [20] is maintained in all variants.

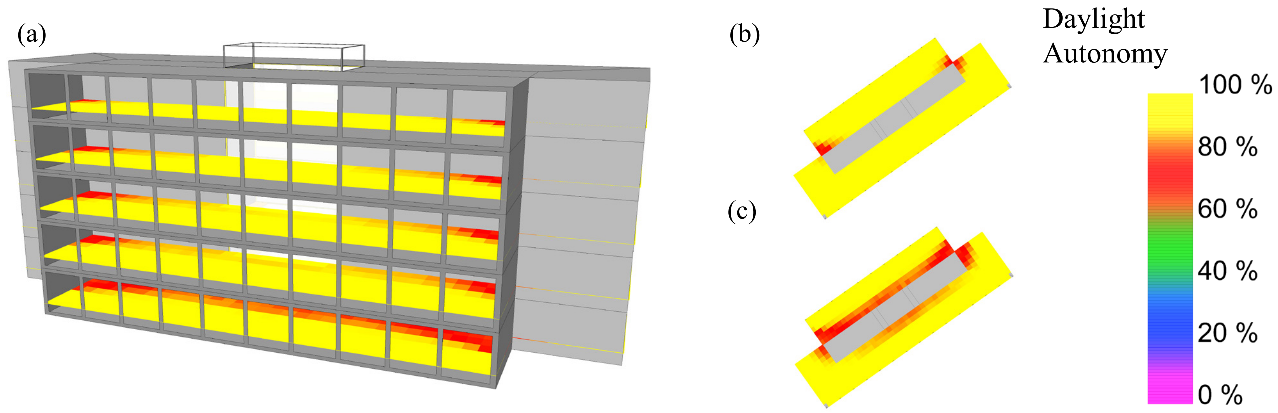

Fig. 4. Daylight autonomy on (a) the north office spaces, (b) fifth floor and (c) first floor

It is worth noting that TRNLizard accounts for daylight controlled artificial lighting and shading controls. Artificial lighting is switched off when the desired amount of illuminance for workplace of 500 lux is met with natural light, and switched on again when the value goes below the required amount of 300 lux. However, if the amount of radiation from the sun exceeds a comfortable amount, leading to overheating and discomfort in summer, the external shading is activated. These additional controls in the design tool allow simulation of a more representative behavior. In practice, shading is activated in office buildings to protect from glare, and artificial lighting is switched on even though there is enough daylight outside.

Evaluation Focus 2: Energy Consumption. The annual heating demand is 17 kWh/m²a. This value is optimized and remains almost the same for all three variants, as the case study only focuses on measures that reduce cooling demand. Fig. 5a shows that nocturnal natural ventilation reduces the annual cooling demand by 55%, from 21 kWh/m²a to 9 kWh/m²a for the case study in Germany. The variation with or without wind shows a minor impact on the annual cooling consumption from 9.3 to 8.9 kWh/m²a; however, the two cases should be compared based on ventilation and comfort.

Another question of interest is how much night ventilation affects peak demand, which is often the determining factor for sizing mechanical equipment. Natural ventilation in variants 2 and 3 occur during night time, while maximum cooling demand happens during the day when it is hot and internal gains due to occupants and electrical devices are great. Fig. 5b illustrates that peak cooling demand is reduced by 15% due to night flushing. The peak sizing could be further reduced with natural ventilation during the day, as a topic for future studies.

To validate the claim that the passive measures proposed in this paper offer both energy savings and a healthy, comfortable workplace, several studies of a conventional building that is mechanically ventilated were performed to determine the glazing ratio that would achieve the same level of energy savings. It is worth noting that reducing the window-to-wall ratio reduces both heating and cooling, and possibly daylight quality depending on the extend of glazing ratio reductions. It is determined that for a fully mechanically ventilated office to achieve energy saving comparable to a building with hybrid ventilation, the window-to-wall ratio needs to be cut down to 20%, yielding an annual end-use heating and cooling of 7.3 and 15.1 kWh/m²a, respectively, not accounting for primary energy conversion. This is because without night flushing, the exposed concrete inside basically carries the heat from one day to another, without the opportunity to cool down at night. While a 20% window-to-wall ratio grants great energy savings, it negatively affects daylight and connection to outside, and consequently, the occupant health and wellness.

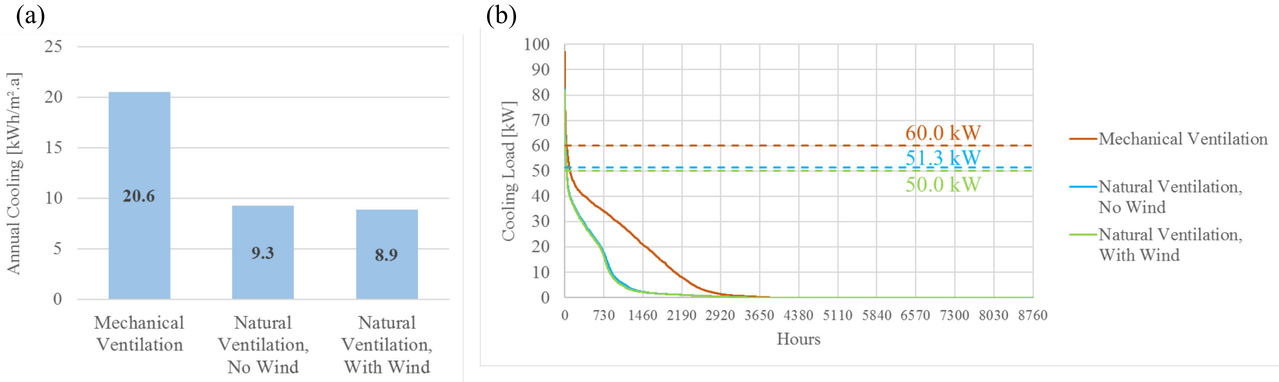

Fig. 5. (a) Annual cooling demand [kWh/m²a]; (b) cooling load curve and 99.6% peak demand

Evaluation Focus 3: Ventilation for Cooling and Indoor Air Quality Control. Fig. 6 compares the indoor air temperature of the three variants for an office facing south-east on the top floor in the intermediate season. In the mechanically ventilated case, the air temperature is always maintained above 21 °C. In daytime, with internal heat gains and solar radiation, the air temperature rises and cooling is required to keep it within the comfort range. In the cases with night cooling, the air temperature is allowed to drop below 20 °C at night by bringing in fresh cooler air from the outside through the window openings, cooling down the exposed thermal mass in the offices.

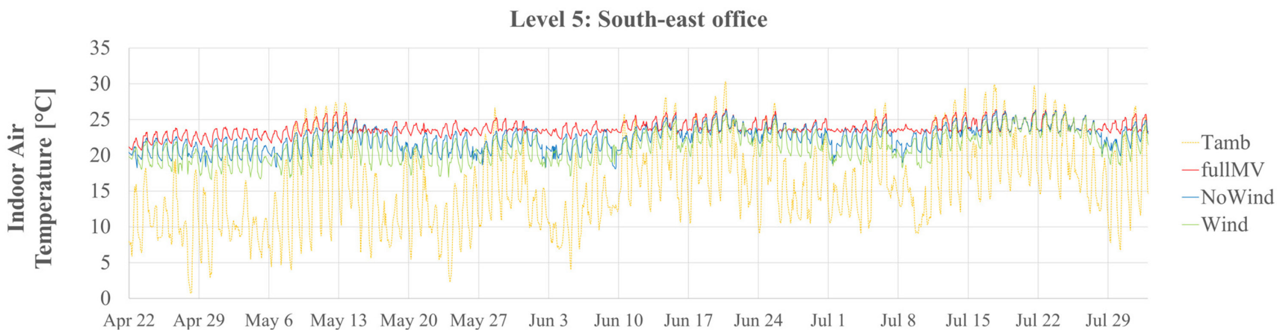

Fig. 6. Comparison of indoor air temperature in the south-east zone for the three variants from April (shoulder season) to July (hot season) on level 5

Due to night cooling, the operative temperature on the first floor remains lower than the mechanically ventilated case by 1 – 5 °C in the morning when occupants arrive and remains lower than the mechanical case throughout the day. Reducing indoor operative temperature, thereby cooling the space, is experienced to a slightly lesser degree on the top level, illustrated in Fig. 6, up to 1 °C warmer than the lower levels; however, it remains lower by 1 – 5 °C than or equal to the mechanically ventilated case. In the hot season, when the night temperatures do not reduce as much, the night cooling potential is reduced on all levels. During the hottest periods, daytime temperatures are very similar for all variants. The air temperature on the first floor is very similar with or without the wind effect. This is because the first floor experiences the greatest stack effect, leading to thermal buoyancy dominating the natural ventilation process. On the top floor, however, the stack effect is reduced, so the wind effect becomes more significant than on the lower levels.

Fig. 7 shows the airflow patterns on the top floor in the intermediate season, as the level with the lowest amount of air mass flow rate. On April 27th, the case with wind experiences backflow in some office spaces, due to a particularly windy situation. It is shown that backflow on upper floors does not occur very frequently, only between 5-15% of the time, and mostly in the intermediate season. The backflow happens when there is an air stratification in the atrium with the air temperature on top lower than the air below it, causing a flow of air in the opposite direction, Fig. 7a. The effect is intensified in the presence of wind, Fig. 7b.

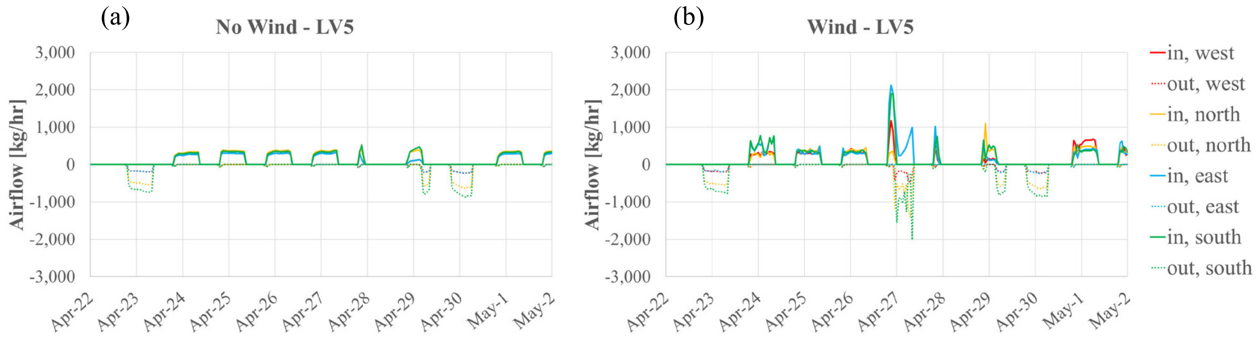

Fig. 7. Ventilation mass flow rate for the 5th floor in the intermediate season; (a) without wind, (b) with wind

Even without wind-assisted natural ventilation, around 350-500 kg/hr of fresh air is supplied to each façade at night time throughout the year, when outdoor temperature is within the acceptable threshold. One commonly argued issue against natural ventilation in multi-story buildings is the effect of stack pressure on natural ventilation. It is argued that at point of neutral pressure, natural ventilation concept does not work very well. Using TRNLizard, with an integrated TRNFlow model, it is shown that with mixing of air in the atrium, this phenomena can be neglected.

Conclusions

It is demonstrated that night time ventilation in an open-office with a central atrium offers considerable savings in annual operational energy cost for cooling as well as initial investment cost by reducing equipment sizing. In the case of the location Regensburg, annual cooling and peak cooling demand are reduced by 55% and 15%, respectively. All office spaces meet the required daylight autonomy of more than 75% per DGNB 15.8/16. Indoor environmental conditions are maintained at a comfortable level according to the adaptive comfort criteria outlined in DIN EN 15251-NA, National Appendix Category II. Air flow simulations show that the 5th and 3rd floor's air inflow can be up to 50% and 75%, respectively, less than the first level. The floor-dependent airflow still leads to total energy consumption reduction.

The concept was validated using TRNLizard, which simultaneously models thermal, daylight and airflow using TRNSYS18, DaySIM and TRNFlow as the background engines. Overall, the advantage of TRNLizard is its ability to connect the power of parametric modeling in Grasshopper with the latest building simulation features of TRNSYS18, as well as considering the mutual dependence of both air flows with air temperatures and daylight with artificial lighting.

The added-value of such integrated simulation tool is validating concepts that put users and their comfort and wellness first. It is not that measures for energy conservation can improve occupant experience and wellness, rather, measures to create an exceptional, healthy environment for occupants, with great connection to the outside and fresh air supply, can drive conservation and energy efficiency. A holistic approach that considers all aspects of design requires an integrated simulation tool that delivers meaningful results.

Future studies should consider modelling natural ventilation during the day for indoor air quality control and supply of fresh air as well as potential cooling. The studies should additionally consider outdoor conditions in an urban environment such as noise and air pollution.

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