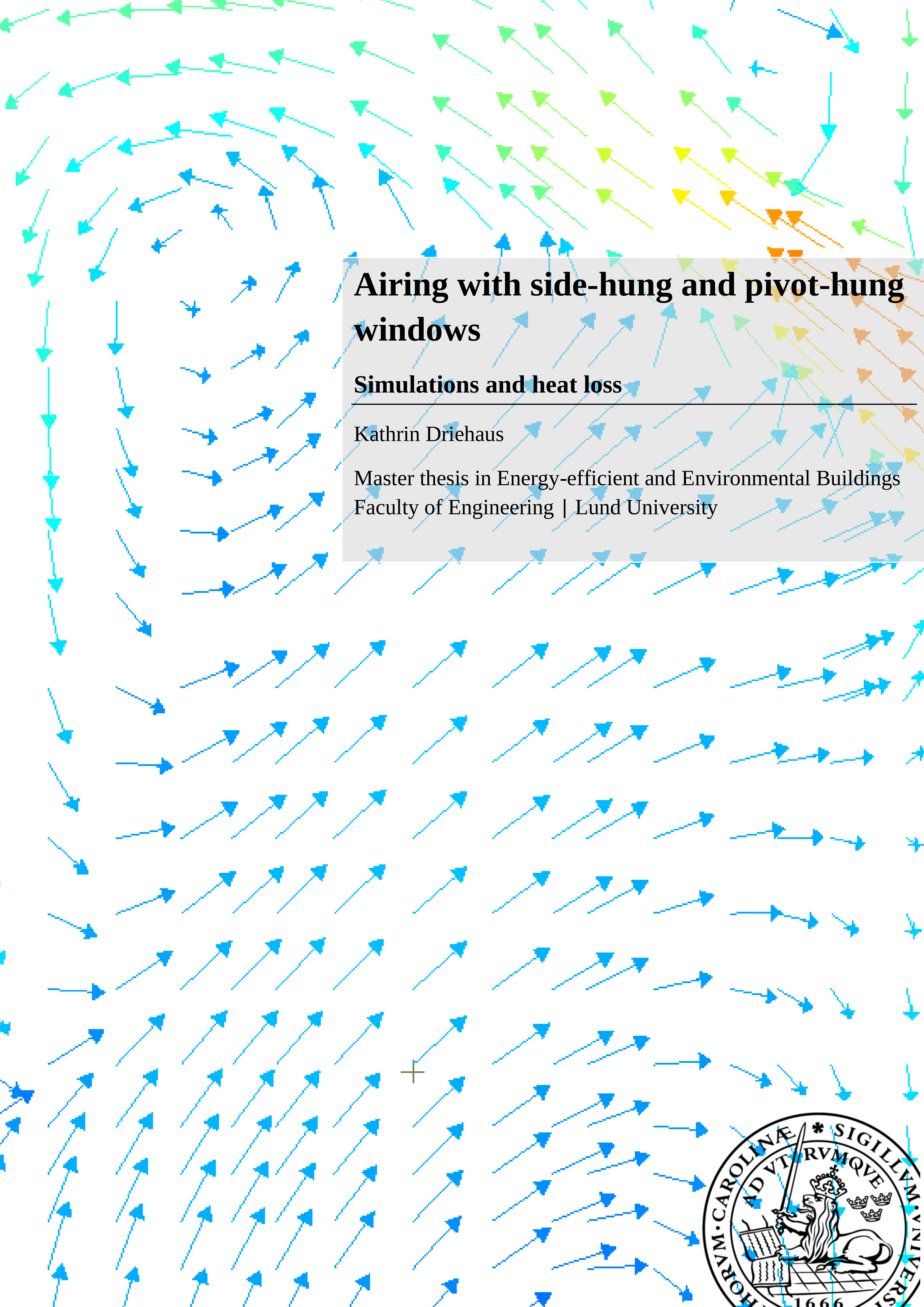

Airing with side-hung and pivot-hung windows

Simulations and heat loss

Kathrin Driehaus

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö and Helsingborg. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Efforts to reduce energy consumption in buildings have increased with the pending impact of climate change. Heat losses through airing behaviours remain a largely unknown factor due to the variety of reasons for opening a window, making generalization difficult. Currently, an estimation of 4 kWh/m^2 heated area for airing heat loss is assumed in Sweden. Additionally, the resulting airflow from opening a window needs to be quantified under various conditions to find a resulting heat loss, which has been done using on-site measurements and computational fluid dynamics (CFD). The aim of this study was firstly establishing air flow data for different opening angles and temperature differences for two rooms with two different window types, the first being side-hung windows and the second pivot-hung windows. For this, transient simulations in the CFD software Simcenter Flovent were performed, with additional measurements using CO_2 as a tracer gas taken in the room with pivot-hung windows to allow for a very limited validation. Secondly, several selected data sets of window opening angles throughout the year taken from apartments in southern Sweden were analysed. Thirdly, yearly airing heat loss was calculated by pairing the air flow data with angles and temperature differences from the user data. As the selected user data sets were not deemed representative, additional parametric schedules were created for the yearly heat loss calculation which depended on various parameters such as opening angle, duration, frequency, and time of day of opening. From the CFD simulations, the pivot-hung windows resulted in higher airflow, but it was unclear whether this was due to the larger window size or the different construction. It also seemed to allow for more efficient air exchange when cross-ventilating, although this is inconclusive due to the lack of comparability between the rooms. Adding wind increased the air flow significantly. There was some deviation between measurements and simulation results, but they were shown to be in a similar order of magnitude when accounting for errors. The heat loss calculations with user data showed a lot of variation with some scenarios comparable to the recommended value from regulations, while others were significantly off. The parametric study revealed that angle, duration and frequency as contained in the data affect the results significantly, while window size was also identified as a large factor. Future studies should concentrate on evaluating additional user data in order to identify further different patterns and driving factors on window opening which could be integrated into simulations.

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1 Introduction

1.1 Background

Reducing the amount of energy needed in various aspects of life has become a widely discussed topic as the consequences of climate change are becoming more real. In 2019, the goal of becoming climate neutral by 2050 was set by the European Union (Directorate-General for Climate Action (European Commission), 2019). Sweden undercuts this target by aiming for a climate neutral country by 2045, which was already established in 2017 (Naturvårdsverket, 2024). The EU guidelines highlight the importance of buildings in the context of energy efficiency, which account for roughly 40% of EU energy consumption. Recent data shows that the ratio is even higher in Sweden, with buildings contributing 44% of total energy use in 2023 (Energimyndigheten, 2024). To reduce this number, efforts are being made to renovate old building stock as well as construct new buildings as zero-energy buildings. This mainly includes structural improvements, such as adding insulation to reduce the heating and cooling demand, as well as upgrading outdated installations to optimize building systems. While these are tangible changes, another large factor that contributes to a building's energy consumption is the behaviour of its inhabitants, which is harder to predict and account for. Besides directly controlling the actual electricity use for appliances and lighting, and the energy used for heating the building, ventilation is another user-based factor which affects energy balance, especially in buildings that do not have a central ventilation system and rely on natural ventilation. Window opening behaviour is diverse as there can be several reasons for opening a window, such as regulating indoor temperature, humidity and general air quality. In combination with an often manually controlled heating system, this can result in an inefficient use of the generated heat due to unnecessary high heat losses through an opened window.

The guidelines for calculating a building's energy efficiency in Sweden are set by Boverkets byggregler (Boverket, 2021a), which is based on both the actual energy use of the building as well as its installed building components and systems. Energy use is defined by the building's primary energy number EP_{pet} which consists of energy demands for heating, cooling, domestic hot water and property energy, with the latter including energy used in the buildings' installed systems and lighting in common areas. To find these values, recommendations for unknown parameters relating to occupant behaviour can be found in Boverkets föreskrifter och allmänna råd (Boverket, 2021b). For window airing, an addition of 4 kWh/m^2 is recommended to be added to the heating demand when there is no available data on this. However, this value is not separate for different building types and does not take into account any installed ventilation systems or different types of rooms. Additionally, user behaviour can well vary even without these differences, which is why it is important to verify the airing heat loss.

Case studies such as the thesis by Bertilsson and Zandi (2023) using a questionnaire to determine airing behaviour have found that it was just as common to open the window only slightly as keeping it half open, with durations ranging from a few hours to having cross-ventilation for a few minutes. The most common frequency was airing every day or almost every day. Through comparing seven apartments in a residential building, they found that duration and frequency of window openings had the largest impact on energy loss, although the airing losses in general affected the buildings energy use less than domestic hot water, indoor temperature and household energy use.

A study by Andersen et al. (2013) in Denmark consisting of 15 dwellings took a different approach with monitoring window opening and closing over 8 months alongside with several environmental parameters. They found that the most important parameters affecting window opening was indoor CO_2 concentration and closing was outdoor temperature, proposing different occupant behaviour models to use in future simulations.

Similar findings were derived from the results of Rijal et al. (2007), showing that the proportion of opened windows in office buildings could be shown as a function of indoor and outdoor temperature, with least openings in winter and most openings in summer, which was used to implement an adaptive algorithm to predict window opening behaviour.

D'Oca and Hong (2014) also determined indoor and outdoor temperatures to be among the main influence on window opening and closing in offices, while also naming the time of day and occupancy as important factors, and concludes with creating two distinct user profiles based on being driven by environmental factors or by habit.

Even when behavioural data is available, another problem arises in quantifying the air flow caused by the window openings under their specific conditions. While there are multiple numerical models for simpler situations, computational fluid dynamics (CFD) simulations have emerged as a relatively new tool that enables processing more complex scenarios.

In Engström (2023) the air flow through a side-hung window was simulated using the software IDA ICE, while comparing the simulation results with measurements using a tracer gas method with CO_2 (Cui et al., 2015). The simulation results were found to be underestimating the measured air flow, with the best match between measurements and simulation air flow at a 90° opening angle.

In an unpublished study by (Johansson et al., 2024), the air flow at different angles through side- and pivot-hung windows was determined through the same tracer gas method, while comparing to a numerical model refined by Nordquist (1998). The measured results were found to be similar to the theory, and additionally the air flow resulting from the pivot-hung window was found to be more linear to the opening angle compared to the side-hung window, suggesting a better control.

Two different window types were also investigated by Heiselberg et al. (2001) which performed lab measurements on bottom- and side-hung windows, proposing that bottom-hung windows are better in winter both for single-sided and cross-ventilation due to lower velocities and higher control, although deemed insufficient for the higher air exchanges needed in summer. The study further identified the dependency of air flow efficiency on opening area, window type and difference between indoor and outdoor temperatures.

Studies using CDF simulations to investigate cross-ventilation at different wind angles and speeds have determined that the wind magnitude (Nikas et al., 2010) as well as the wind incidence angle and window size (Sacht and Lukiantchuki, 2017) are important factors that influence the air flow through windows.

1.2 Objectives

The main object of this study is to gain better understanding of the amount of energy loss that is associated with window airing at certain opening angles. The first part of this is finding data by CFD simulations for the airflow caused by several scenarios of opening angles and temperature differences as well as different layouts of windows being opened. Air flow measurements by help of CO_2 concentrations for a few selected scenarios of the simulations are compared to the simulation results to allow for some verification. Secondly, selected cases of window opening behaviour by opening angle are analysed to identify possible patterns. The user data in combination with parametrically created opening schedules are combined with simulation results to calculate yearly heat losses to be compared extensively, focusing on how the parametric results compare to the user data as well as to the BBR recommendations, and how varying different parameters affects the results.

1.3 Limitations

This thesis is subject to several limitations. The scope of the parametric CFD simulations is limited by the choice of geometry and its fixed window sizes and types, as well as limitations concerning the number of scenarios due to time constraints. The available user data was still incomplete and data sets were chosen according to their usability in terms of measuring errors and not for their applicability to the simulation data. Because of this, additional parametric schedules were created by varying several parameters, the amount of which being limited by the ability to handle that amount of data.

2 Methodology

2.1 CFD Simulation

2.1.1 General

Air flow simulations were achieved in Simcenter Flovent, a computational fluid dynamics (CFD) software developed by Siemens (Siemens Digital Industries Software, 2020). The program enables CFD simulations in a 3D environment which can output predictions for airflow, heat transfer and other building comfort related indices.

For the modelling of CFD simulations, two separate existing rooms in residential buildings were chosen for the purpose of allowing future possibilities of performing on-site airflow measurements to compare to simulation results. The first option featured 4 outward opening side-hung window units each consisting of two parts with flipped opening sides, located in 3 different directions (Figure 1). The second option consists of a room with 2 pivot-hung windows located across a corner from each other. The room also has a door on the same side as one of the windows (Figure 2).

For this study, short term transient simulations of under a minute length were performed, although it could be argued that a steady state simulation with a heat source would represent reality more accurately as windows are generally opened for longer than the transient simulation would account for. However, a problem emerges with keeping the indoor temperature constant across different opening scenarios as the heat source would have to be adjusted. Therefore, the simpler approach of a transient simulation with a consistent indoor temperature was chosen.

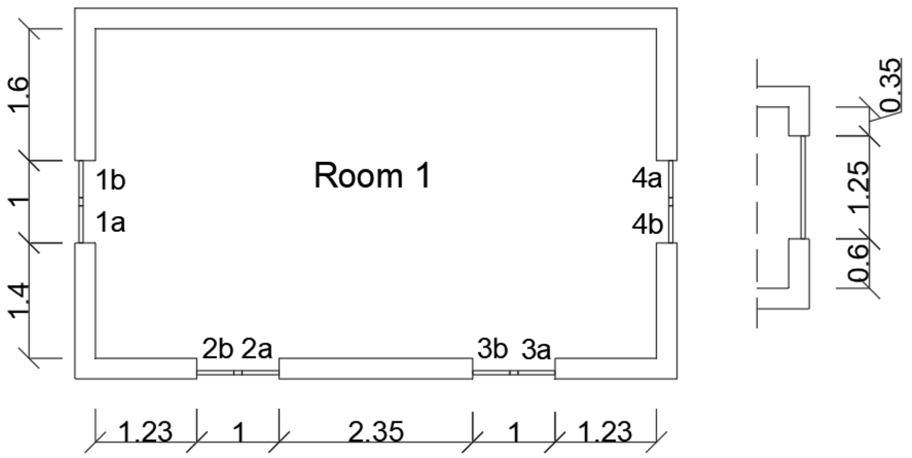


Figure 1. Room layout with side-hung windows.

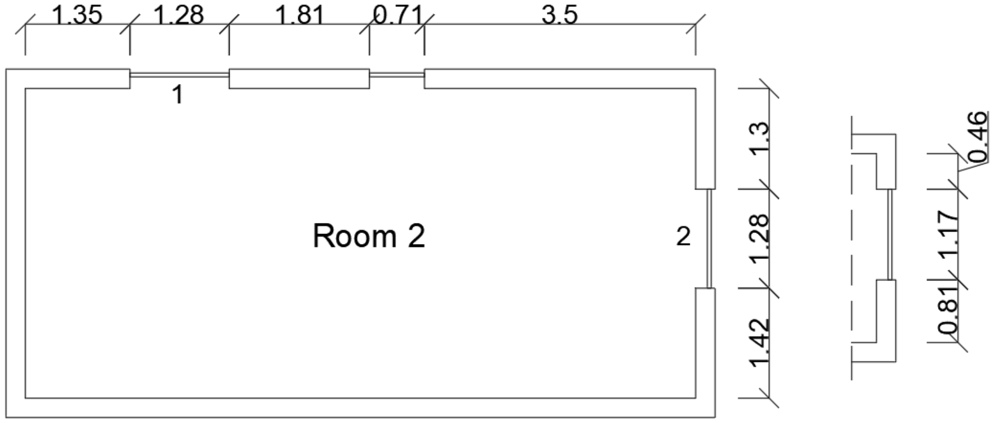


Figure 2. Room layout with pivot-hung windows.

2.1.2 Modelling

To keep consistency, the geometry of the two rooms was modelled similarly in Flovent. The basic geometry was drawn according to the measurements of the rooms. The thickness of the walls was set to 250 mm with the material being chosen as EPS insulation (0.05 W/(m·K)). The insulating ability of walls and other building parts was not chosen with special care as the effect of heat loss through conduction was deemed insignificant due to the short duration of the simulation. All windows were modelled as simplified sloping blocks with a thickness of 50 mm to account for the influence of the frame thickness when opening at small angles. The actual frame was not modelled, however the windows placed as one unit in Room 1 were separated by a mid-post of 50 mm thickness and 100 mm width.

The system measurements exceeded the boundaries of the modelled rooms by at least 3 m on all external facing walls in order to enable air circulation around the building in the simulation. Additionally, it was extended to the bottom by 0.25 m and the top by around 3 m to allow room for modelling the ground as a slab of 250 mm thickness and the upper story of the house by a cuboid of the same footprint as the modelled rooms and a height corresponding to the system boundary (Figure 3). Both cuboids were modelled in the same insulation material as the building's other parts. This resulted in system dimensions of 13 m · 8 m · 4.95 m for room 1 and 12 m · 7.5 m · 5.19 m for room 2. The system was designed this way to give sufficient room for the airflow patterns outside the building in order to give more realistic results.

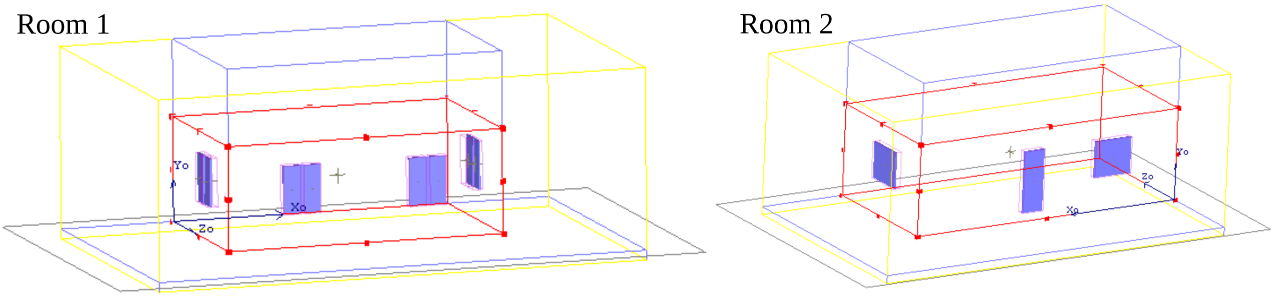


Figure 3. Modelled geometry in Flovent for Room 1 (left) and Room 2 (right). The red line represents the room outline, the yellow the system boundary and the blue additional obstructions.

The grid for the simulation was set to a minimum size of 0.01 m and a maximum size of 0.3 m for the basic environment, while the maximum size was decreased to 0.02 m for 0.4 m outside and 0.7 m inside the windows to increase grid density. The grid was adjusted to be as fine as possible to ensure accuracy in the significant areas around the windows while keeping a reasonable simulation time.

2.1.3 Transient simulation

A transient simulation was set up by adding a subdomain, or separate part of the system, of the same size and location as the enclosure where the initial temperature was set to 20 °C as opposed to the colder outdoor temperature to create a temperature difference for the simulation. Then, transient solution was activated and edited to include 40 time steps of 1 second length each. This was separated into 2 periods of 20 seconds each, where the first would run for the base case with all windows closed, while the second period would be initiated from the base case, applying the various window opening scenarios as a parametric study. This was necessary since the subdomain with the initial temperature of 20 °C was not available when performing parametric scenarios in the program, so the time point after the first 20 seconds served as the starting point with the correct temperature conditions for the scenarios. The final result was then taken after 40 seconds of simulation in total, with 20 seconds of opened window.

To assess the results, monitor points were set up in the centres of each enclosure, serving as a checkup point to control the indoor temperature across the different scenarios, and each window opening, where the velocity through the window was logged. Additionally, a volume region was added in each window opening when said window was opened. This was set up to measure the volume flow in the direction through the window, with the logged parameters being high and low volume flow in both flow directions.

2.1.4 Scenarios

The parametric study includes a variety of scenarios for the window openings. Room 1 was tested with both one and two parts of a single window unit opened as well as two window units with only one side opened directly across from each other and around a corner from each other. In room 2 with its simpler window layout, window opening was tested for a single opening as well as cross-ventilation across the corner. For the latter, a scenario was run with a 5 m/s wind blowing towards the first window as well. An overview of the scenarios is found in Table 1.

Table 1. Window combinations for simulation.

Scenario index	Description	Opened windows
Side-1	Side-hung, room 1, one side of one window unit	2b
Side-2	Side-hung, room 1, both sides of one window unit	2a, 2b
Side-3	Side-hung, room 1, one side of two window units	2b, 4b
Side-4	Side-hung, room 1, one side of two window units	1b, 4b
Side-5	Side-hung, room 1, both sides of two window units	2a, 2b, 4a, 4b
Pivot-1	Pivot-hung, room 2, one window	1
Pivot-2	Pivot-hung, room 2, two windows	1, 2

For each different window opening scenario, opening angles were changed in a series of 1°, 2°, 3°, 4°, 6°, 8°, 10°, 15°, 20°, 30°, 45° and 90°. For the pivot hung windows the opening axis of the window was additionally moved downward according to its opening angle due to the way the opening mechanism works. A data series from measurements was created for this purpose (Table 2).

Table 2. Downwards movement (n, in fraction of window height) of the hinge relative to opening angle (in °) for pivot-hung window.

angle	0	5	10	15	20	25	30	35	40	45	50	60	70	80	90
n	0.00	0.00	0.00	0.01	0.03	0.04	0.07	0.08	0.12	0.16	0.19	0.25	0.32	0.38	0.44

Outdoor temperatures were varied between -10°C, 0 °C, 5 °C, 10 °C and 15 °C to cover the broad majority of temperature differences occurring in southern Sweden, while the indoor temperature was kept at a constant 20 °C to create data for various temperature differences.

2.2 On-site measurements

For comparison with the airflow results on Flovent, the air exchange rate in room 2 was measured using the CO_2 tracer gas concentration decay method (Cui et al., 2015). For this, an Extech SD800 Data Logger measuring CO_2 concentration, humidity and temperature was placed centrally in the room at approximately 1.5 m height. CO_2 was then added to the room up to a concentration of 4000 ppm to 5000 ppm. Additionally, a heater kept the temperature in the room between 27°C and 32 °C to create a temperature difference to the outside air. A fan was turned on during this process to mix the air until the values on the logger stabilized and started to decrease again slowly. Then the fan was turned off, the window opened to its specified angle and the room was left undisturbed until the CO_2 concentration decreased at least to half of the starting concentration.

The procedure was done on a sunny day with little wind (1-5 m/s, (SMHI)) and outdoor temperatures between 14 °C to 16.5 °C. During the process, the outdoor temperature was logged every five minutes in order to find the temperature difference to the indoor temperature. This was needed to compare the measured air exchange to the Flovent airflow results for each scenario.

Due to time constraints, only the air exchange for opening angles of 5°, 10° and 30° was investigated. This was repeated for both a single window being opened as well as two windows opened at the same time to study cross flow.

The air exchange rate was found by plotting the natural logarithm of the CO_2 concentration, which was corrected for the outside concentration determined by measurements taken outside, and fitting a linear curve to the values, where irregular values in the beginning and end of each measurement were excluded. The declination of the curve represents the air exchange rate. To find the air flow rate in m^3/s, the air exchange rate in 1/h was multiplied by the volume v of the room in m^3 as shown in Equation 1. To account for the infiltration of the room, the air flow respectively air exchange rates were corrected by the resulting rate of a closed window measurement. The equivalent simulated air flow rate was found through linear interpolation between the known simulated results.

$$q = n \cdot v \cdot 3600\ \frac{s}{h} \tag{1}$$

2.3 Occupant behaviour data

The airing behaviour data was received from ongoing data measurements logged across a year using newly developed angle sensors. These consisted of two types. The first relies on the magnetic field to calculate the opening angle from its position and was used for windows with a vertical opening axis, while the second uses an accelerometer to determine the angle when the opening axis is horizontal. Of these two, the data provided by the latter proved more consistent and less prone to disturbances.

The received data was already calibrated using an on-site calibration process where each window angle was adjusted manually and compared with the result from the sensor. All logged values were adjusted according to the resulting calibration curve.

Table 3. Overview of used angle data sets.

Data set	Description	Location	From:	To:
H1	Bedroom window	Höör	24/05/2023 06:27	14/03/2024 15:27
H2	Bathroom window	Höör	22/05/2023 11:52	14/03/2024 12:41
L1	Bedroom window	Lund	26/05/2023 15:35	19/12/2023 02:57
L2	Kitchen window	Lund	26/05/2023 14:40	12/03/2024 16:06

Four data sets from 2 different locations were selected based on the usability and applicability of the data (Table 3). Logger data for indoor temperature, relative humidity and CO_2-concentration was also available for these locations. Outdoor temperature data was found for the corresponding times from SMHI. The data was further processed by removing duplicates and scaling into a minutely timetable where necessary, using the MATLAB "retime" function. This formed a basis for investigating the relationship between opening angle and outdoor and indoor temperatures, relative humidity, CO_2-concentration and time of day as well as the frequency of openings.

2.4 Calculation of energy use

2.4.1 Conversion of airflow to heat loss

From selected scenarios of the simulation results, a table was put together to include air flows for in- and outflow for each scenario of the given angles and temperature differences. To get the correct air flow for a specific angle and temperature difference, bilinear interpolation was used on these tables. Heat loss was calculated using the specific heat c_p and density ρ of air, air flow q and temperature difference T_{in}-T_{out} (Equation 2). Air density was obtained using the ideal gas law (Equation (3), with p as air pressure, R_{sp} as the specific gas constant for dry air and T as Temperature. For the outflow heat loss of the simulated air flow, air density was calculated using the indoor temperature, while the inflow heat loss used the air density of the outdoor temperature. The average of these two calculations gave the final heat loss results.

$$Q = c_p \cdot \rho \cdot q \cdot (T_{in} - T_{out}) \tag{2}$$

$$\rho = \frac{p}{R_{sp} \cdot T} \tag{3}$$

This calculation procedure was applied to different window opening schedules to find the energy loss in kWh resulting from window openings during the year.

2.4.2 Parametric study

Different parameters were varied to create a parametric study of opening schedules. Window opening was defined by the time of day when the window was being opened, the frequency (daily, every other day, biweekly, weekly) of opening occurrences, the duration of the window opening in minutes, and the opening angle. An overview of the different parameters is shown in Table 4. The combination of these parameters resulted in 1440 different scenarios to be compared. These scenarios were repeated with two selected scenarios from the side-hung and pivot-hung window results (Side-1 and Pivot-1) corresponding to a simple, single-sided opening. For the outdoor temperature, dry bulb temperature for Lund (Climate.OneBuilding.Org, 2023) was used, while two different sets of indoor temperature where created, one with a constant temperature of 21 °C (according to regulations (Boverket, 2021b)), and another with a reduced temperature of 18 °C between 9 pm and 6 am to while keeping 21 °C during the rest of the day.

Table 4. Parameters and their different variations.

angles/°	5, 10, 15, 20, 30, 45, 90
durations/min	5, 10, 20, 30, 45, 60, 120, 180, 360
frequency	every day, every 2nd day, every 3rd day, once a week
start times of opening	12 am, 6 am, 12 pm, 6 pm

The schedules were created iteratively from the mentioned parameters in MATLAB, resulting in arrays containing an entry for every five minutes of the year which were stored in a 4-dimensional matrix. The calculations from 2.4.1 were applied to each of these arrays using the same iteration logic.

2.4.3 Use of real data

The results from the parametric window opening schedules were compared to the selected schedules created from the received user data. To make the data usable, a threshold of 2° for H1 and L1, 5° for H2 and 6° for L2 was applied to set the angle values around 0° to a true zero, as there were inaccuracies of the measurements and calibration in the data that resulted in small angles being registered when the window was closed. Additionally, opening angles above 90° were set to 90° to fit the air flow data, since 90° is already fully open and it should not make a difference if the window is opened further, even though possible.

The calculations were done similarly to the parametric study, except that the schedule contained every minute of the year and the measured indoor temperature profile from the data was used instead of a generated one. Similarly, the outdoor temperature was not from a weather file, but the actual temperatures during the time period from SMHI.

3 Results and discussion

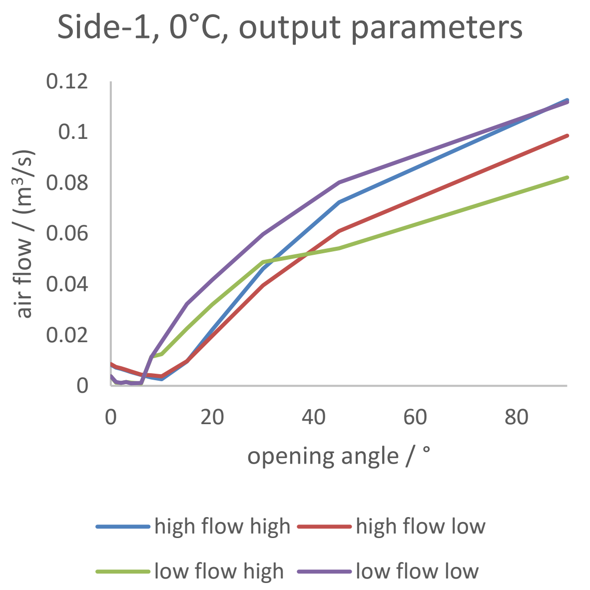
3.1 Airflow

3.1.1 CFD Simulation

3.1.1.1 Output parameters

Due to some uncertainty in how the software calculates the available output parameters called "high volume flow high", "high volume flow low", "low volume flow high" and "low volume flow low", they were compared for both a single opening of the pivot-hung window and the side-hung window. It was determined that high/low flow high and high/low flow low correspond to the direction of the flow through the window, namely the in and out flow, while the difference between high flow high/low and low flow high/low was assumed to be the result of different calculation models, although this could not be validated.

As can be seen in Figure 4, for the side hung scenario the low flow results divert more at the higher angles than the high flow results, and especially the out flow of the low volume flow is much more prone to irregularities than the other outputs. Compared to that, the pivot-hung results show a bit of a larger difference at lower angles between low flow and high flow, but the difference between in and out flow in each case is almost non-existent, which indicates that this window construction allows for a less obstructed flow of air. For both window scenarios, the high flow results yield a slightly steeper curve than the low flow with lower initial values.



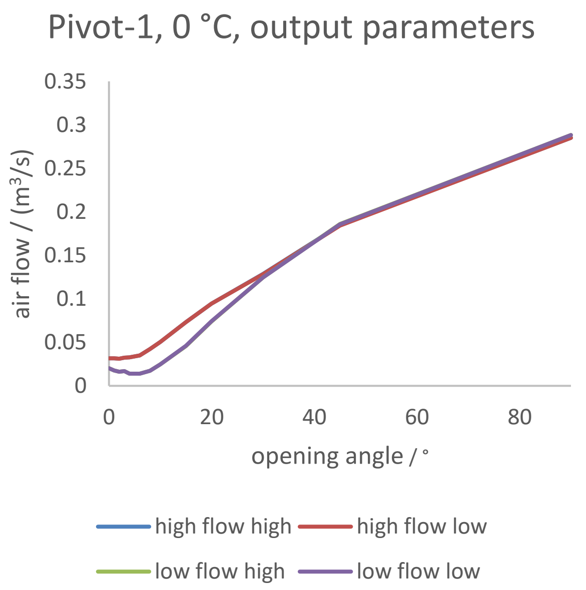


Figure 4. Output parameters for side-hung and pivot-hung windows in a single sided opening at 0 °C outdoor temperature and different angles.

An interesting situation presents itself at very low angles between 0° and 10°. For both side- and pivot- hung windows, the air flows remain more or less stagnant with even a slight decrease (especially for the high flow results) from 0°. One likely explanation for that could be the inaccuracy of the window model combined with the chosen slab thickness of 5 cm for the window. Due to this, the angles up until 8° - 10° hardly result in an opening at all, which means that the registered flow should be similar to the flow at 0°. While we would assume there to be no flow at 0°, the result likely stems from the volume region used in the program for measuring the flow being the size of the window opening in the walls and not the window itself, which would mean that air streaming along the window, as illustrated in Figure 5, will be registered as air flow even though it is not exiting the room. For the closed window, this could be mitigated by using the window object as the measuring volume region, but as soon as it is slightly opened a small falsified air flow will be registered resulting from air flowing along the window rather than outside. For larger opening angles this problem is likely neglible. To make the results usable for smaller angles, values for low angles used in the calculations in 3.3 are based on linear interpolation between the 10° result and zero.

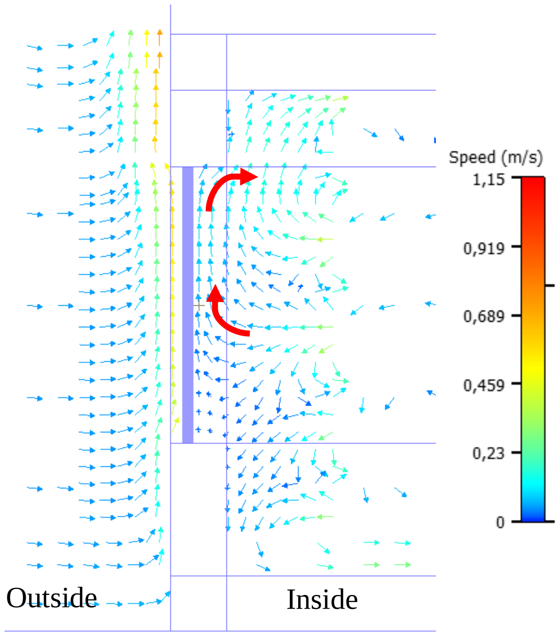


Figure 5. Air flow around a closed window, seen from the side. The red arrows mark the flow registered when the window is closed.

As no clear conclusions can be drawn from the assumed different air flow calculation models for high and low volume flow, the further air flow results and comparisons are based on averages of both models for in- and outflow.

3.1.1.2 Window type

When comparing the different window types, the curve between different angles is very similar (Figure 6). However, in terms of absolute values, the air flow is much higher for the pivot hung window. To reach a similar air flow as the pivot-hung window at 20°, the side-hung window needs to be opened at 50° to 70° depending on the temperature difference. This can partly be explained by the larger area, as the windows have a similar height, but the width of the pivot-hung window is about three times larger than the width of the side-hung window. Although air flow is not exactly linear to the window area, the given formula by Awbi (1991) suggests that the influence of the width is somewhat linear, while the height has a larger influence. Therefore, due to the similar heights, Figure 7 plotting the airflows normalized by window area should be somewhat representative, showing only a slight discrepancy in favor of the pivot hung window. In order to get a definite result on this, the simulation should be repeated with multiple window sizes for each window type.

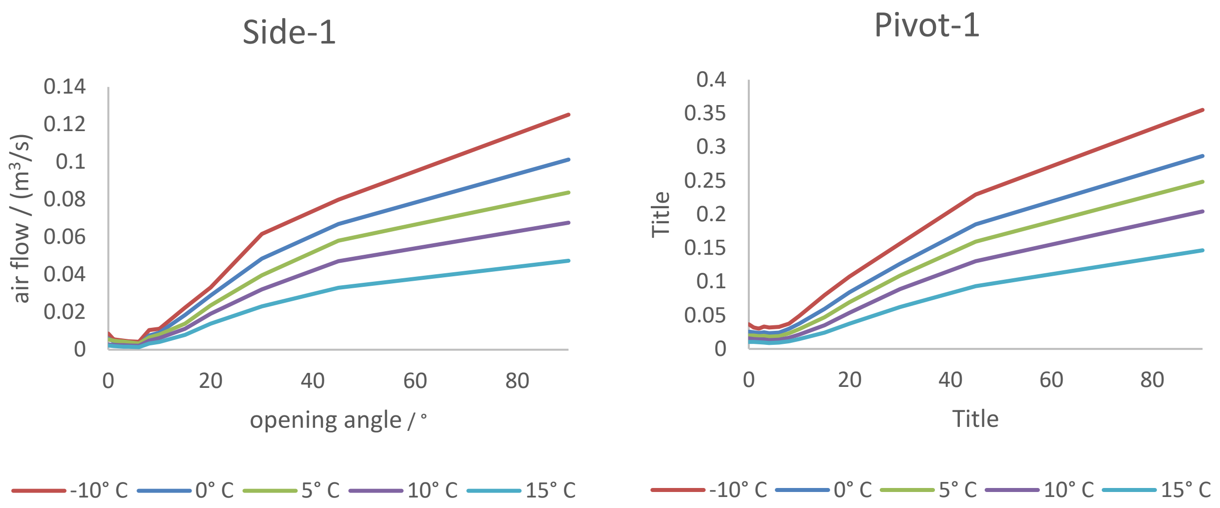


Figure 6. Comparison of airflow corresponding to different opening angles and outdoor temperatures for side- und pivot-hung windows.

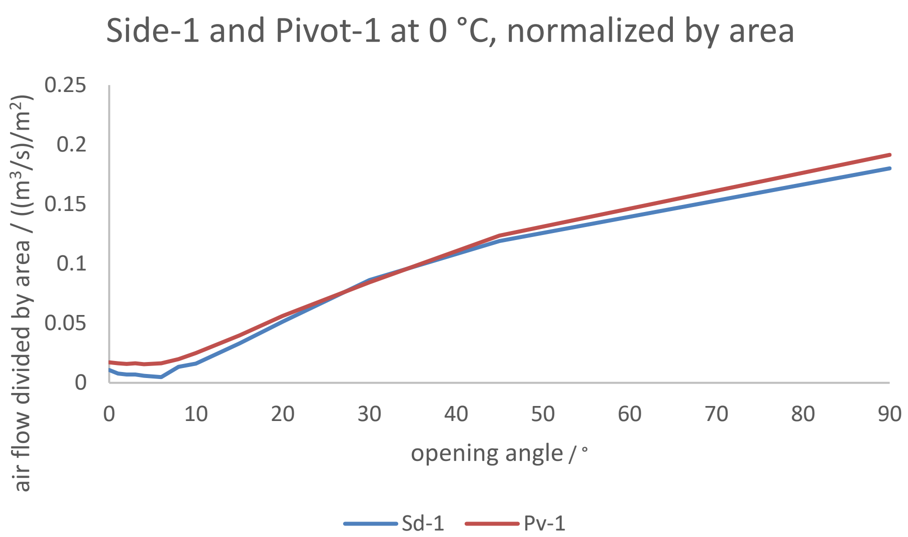


Figure 7. Comparison of airflow corresponding to different opening angles at 0 °C outdoor temperature for side- und pivot-hung windows, normalized by window area.

Figure 8 shows the different air flow patterns at 30° opening for each window type, which are different due to the opening styles. It could be argued that the horizontal hinge combined with the downward offset of the pivot-hung window results in a more efficient air exchange pattern due to the larger opening space at the lower and upper parts of the window compared to the triangle shaped openings which are at the bottom and top of side-hung windows. However, the actual airflow values are inconclusive on this due to the aforementioned lack of comparability.

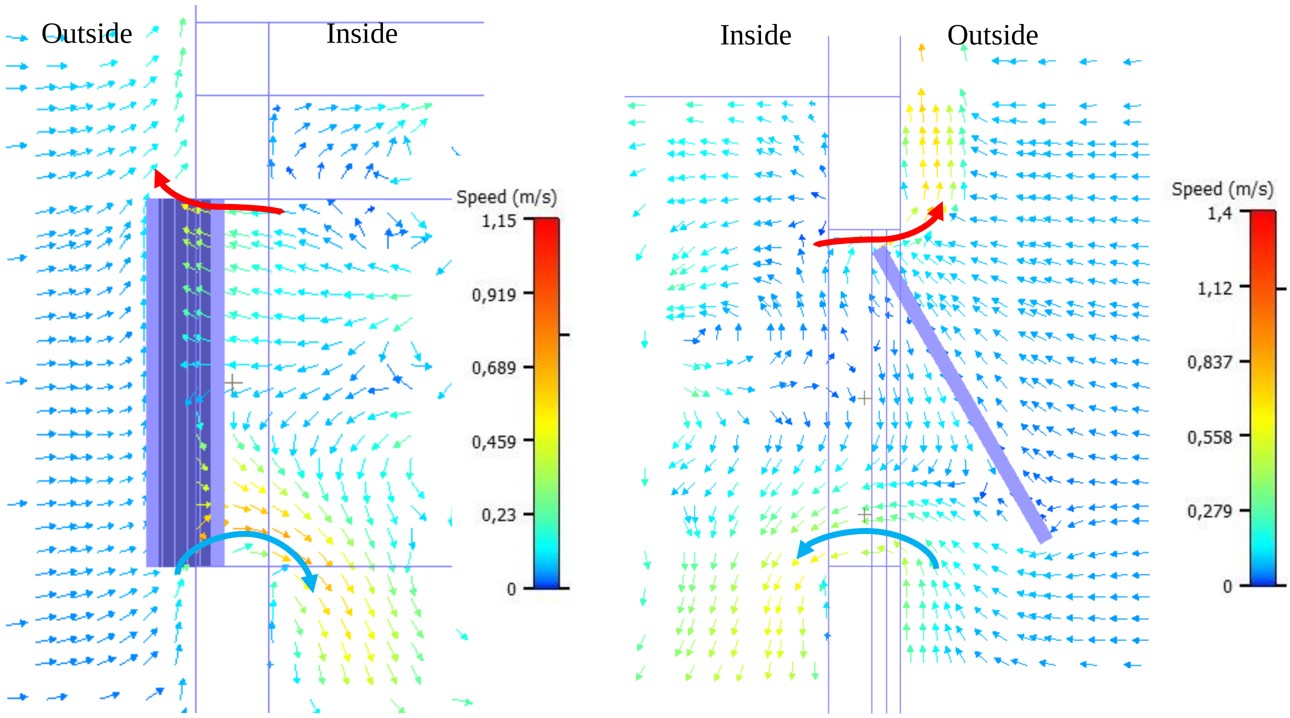


Figure 8. Airflow pattern of side-hung (left) and pivot-hung (right) windows at 30° opening and 0 °C outdoor temperature, seen from the side. The large red and blue arrows show outflow and inflow respectively.

3.1.1.3 Side-hung window unit – one part vs both parts

When comparing opening one or both parts of a side-hung window unit, the flow is roughly doubled for the latter, although it is a bit higher per window at the highest angles (60° - 90°) and a little lower around 20° and 40° (Figure 9). The latter could be a result of the mid post diverting the flow at the low angles, which should not make a difference at high angles. Additionally, the way the windows are mirrored next to each other actually results in a smaller opened area than opening two windows further away from each other. This is because unless the windows are opened very far apart, the rectangle-shaped opening area on the side of the windows overlap when the windows are close together, thus making the total opening area smaller than if each window has their full opening area.. The slightly higher flow at high angles could possibly be attributed to generally higher flow within the room due to the larger opening areas.

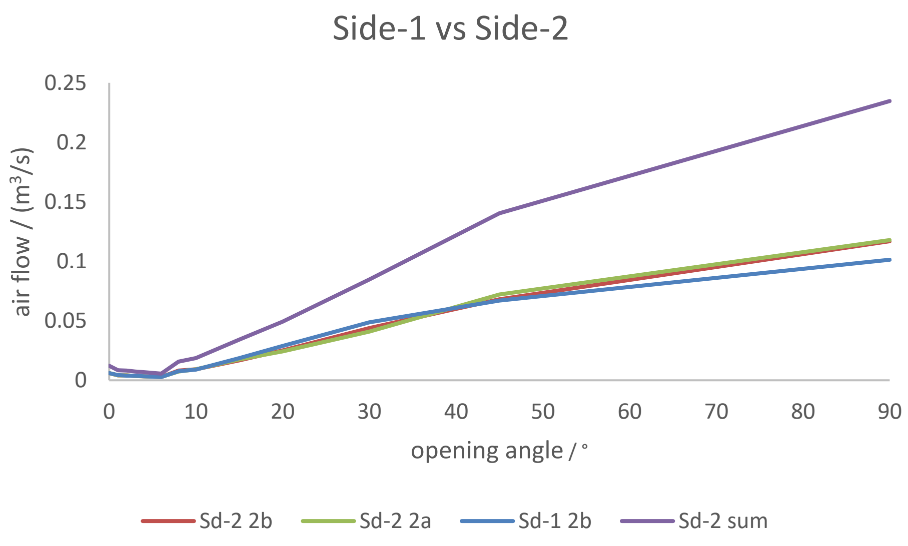


Figure 9. Airflow according to opening angle for one part and both parts of window unit, by window side and sum at 0 °C outdoor temperature.

3.1.1.4 Cross ventilation

Cross ventilation without added wind has roughly the same effect as opening more windows or a larger window area, as the flow for each window was approximately the same as for a single window opening, resulting in an overall doubled flow. This applies to both side-hung and pivot-hung windows (Figure 10).

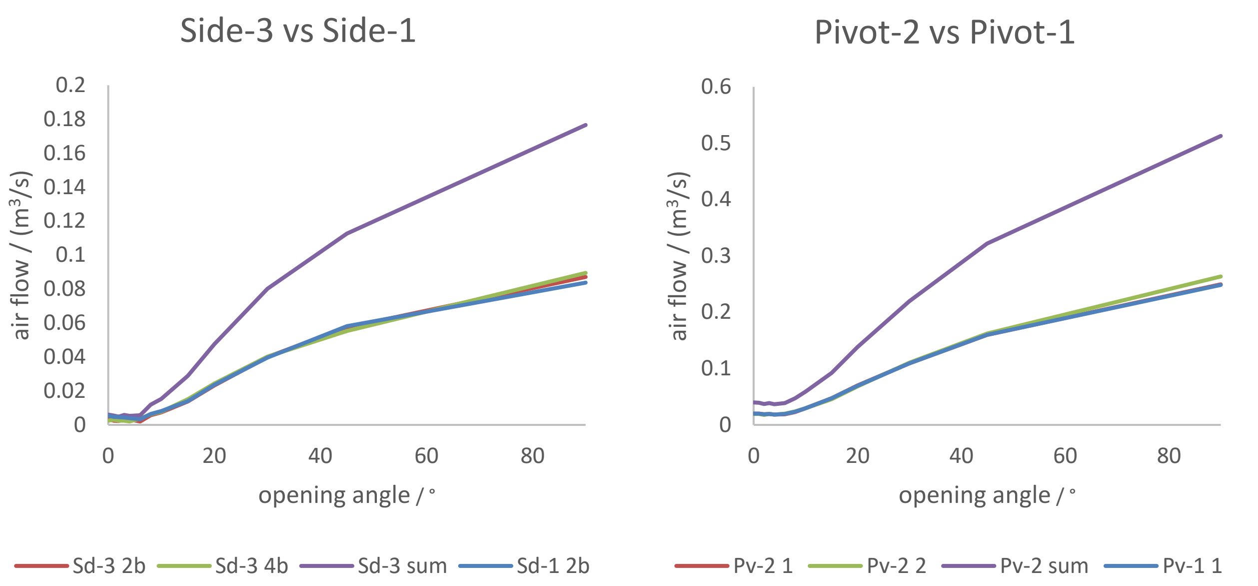


Figure 10. Airflow according to opening angle for two opened windows, side-hung (left) and pivot-hung window (right).

For the side-hung room, an additional comparison was done between windows opened across a corner and windows located opposite from each other. Figure 11 shows that no difference between the two cases is visible.

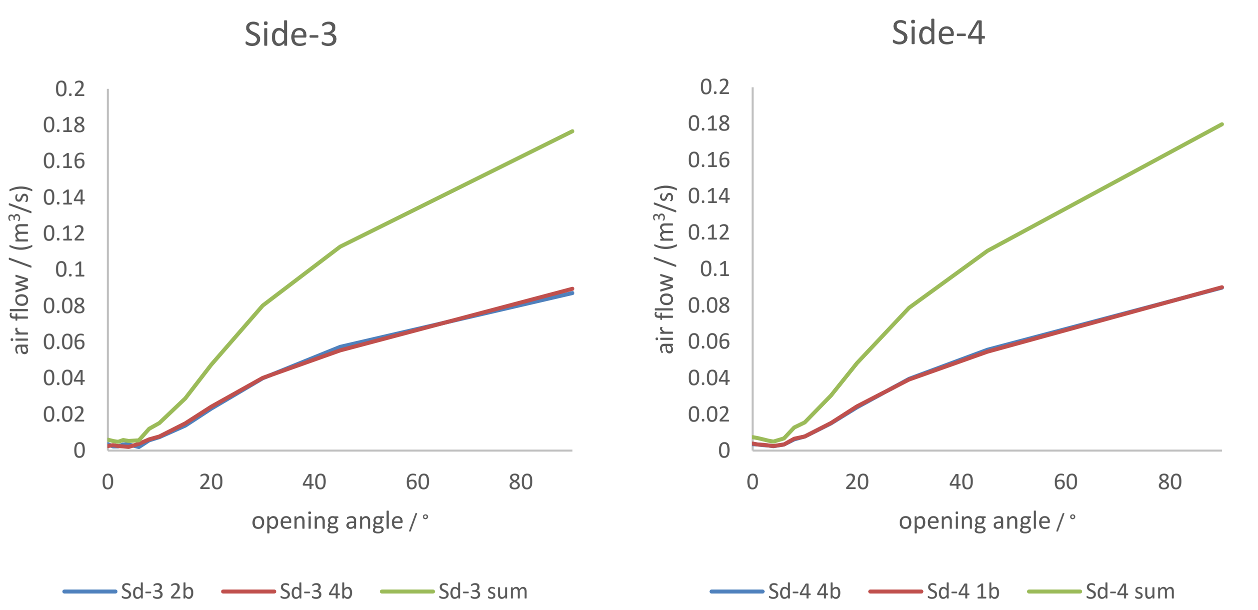


Figure 11. Airflow according to opening angle for two windows opened across a corner (left) and opposite from each other (right).

3.1.1.5 Cross ventilation with wind

Adding wind to the crossflow scenarios results in a significant increase in airflow. The comparison is made between the average of the flow for the two windows for the wind scenarios and the sum of the flow of both windows for the no wind scenario (Figure 14). This is due to the fact that without wind, the flow is temperature driven and each window causes air flow by itself, while the wind produces a clear pattern of the air entering through one window and exiting through another (Figure 12 and Figure 13), suggesting that the entry and exit flow should be the same and therefore represent the exchanged air.

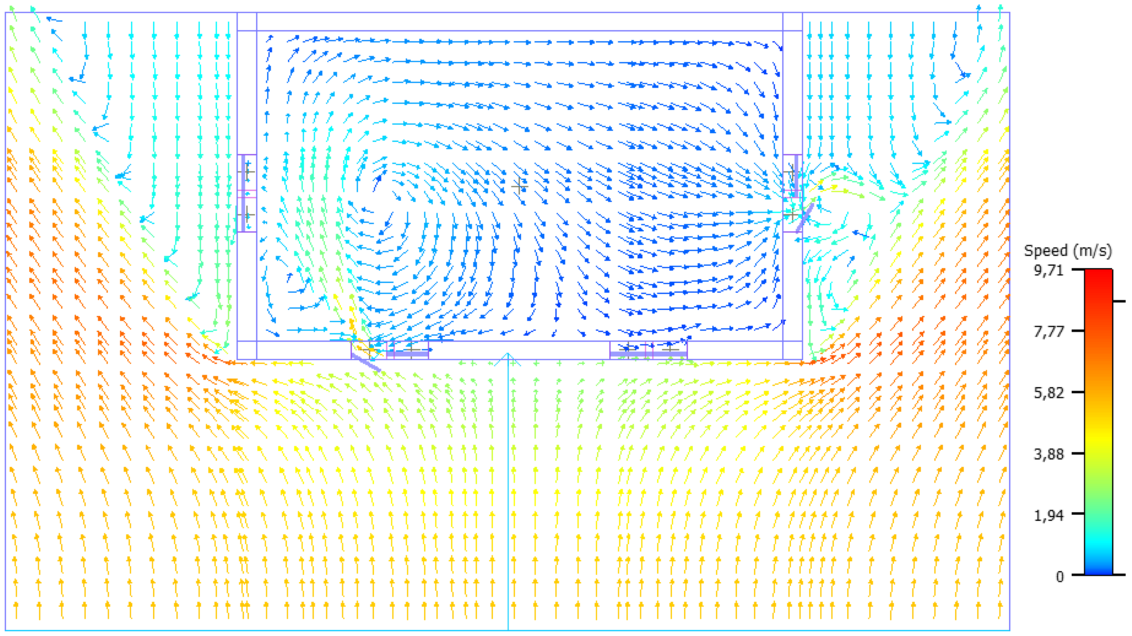


Figure 12. Top view of air flow patterns for Side-2 with added wind.

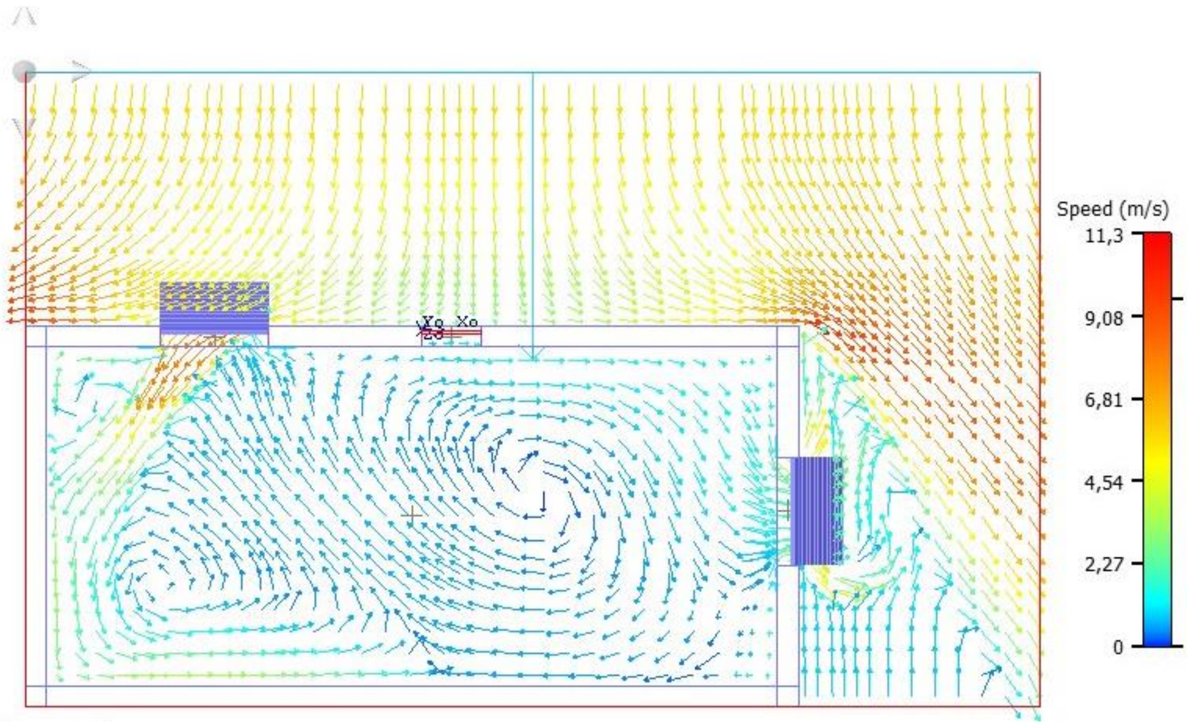


Figure 13. Top view of air flow patterns for Pivot-3 with added wind.

Numerically, the addition of wind corresponds to an increase in airflow by a factor of around 6 for the room with side-hung windows and 11 for the room with pivot-hung windows. Additionally, the curve for the pivot-hung window is steeper than for the side hung theory supporting the theory that the pivot-hung window construction allows for a more efficient air exchange at least for wider angles when an opening occurs at the top of the window, since this results in a larger opening area both at the top and bottom of the window. However, this should be tested with more comparable window sizes and rooms and different wind velocities as well as other factors such as the incidence angle of the wind. It is also to be noted that realistically, a wind blowing steadily and orthogonally towards the window is probably a rare occurrence, as the wind flow will usually be diverted by surrounding buildings and other obstructions.

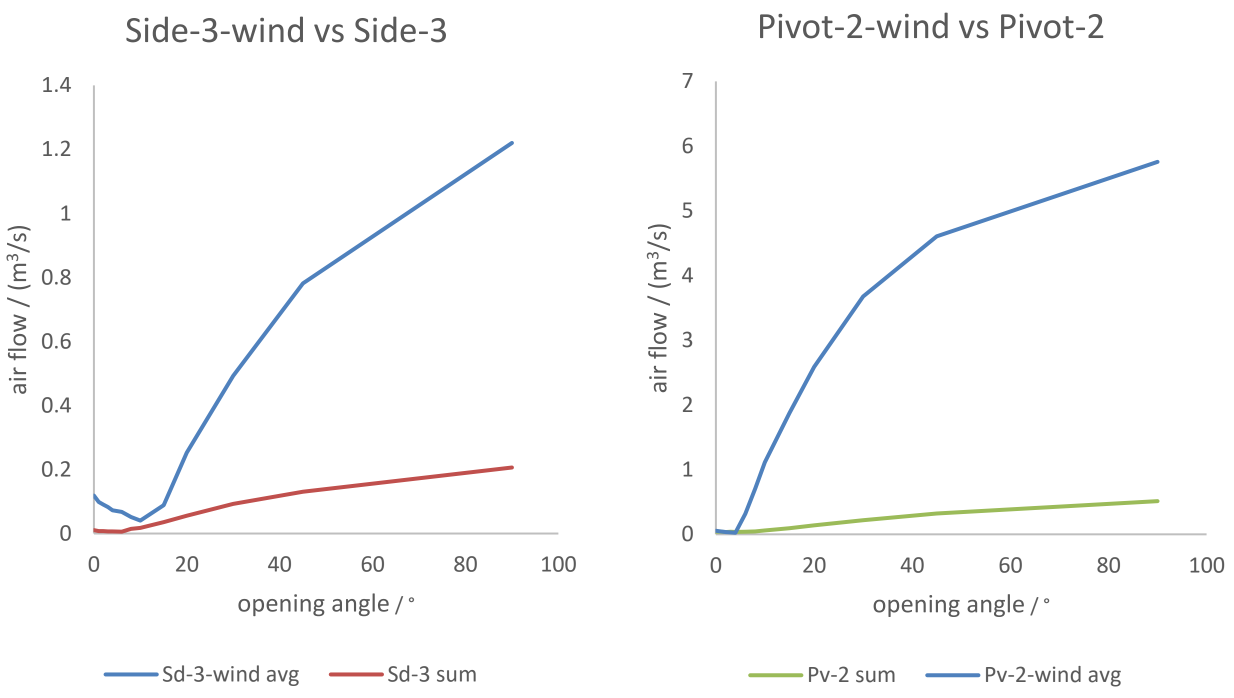


Figure 14. Comparison between side-hung and pivot-hung windows for cross-ventilation with added wind.

3.1.2 Measurements

The measurement results are plotted in Figure 15. As can be seen from the graphs, the difference in the air change rate for 5° - 10° angles is relatively small for a single sided opening, while it increases quite significantly at 30°. For the cross-ventilation scenario, the exchange rate increases by around 10 % for 5°, is more than quadrupled for 10° and roughly doubled for 30°. Except for the high rate at 10° these values approximately correspond to the percentual differences in the simulation results. This suggests either widely varying conditions or user error at the 10° measurement. It is possible that the high result is caused by increased wind during that specific time window, or alternatively the fan used to distribute the CO_2 in the room might have been kept running by accident. The smoothness of the line between the measurements suggests the latter, as sudden gusts of wind should have caused some irregularities in the measured CO_2 concentrations.

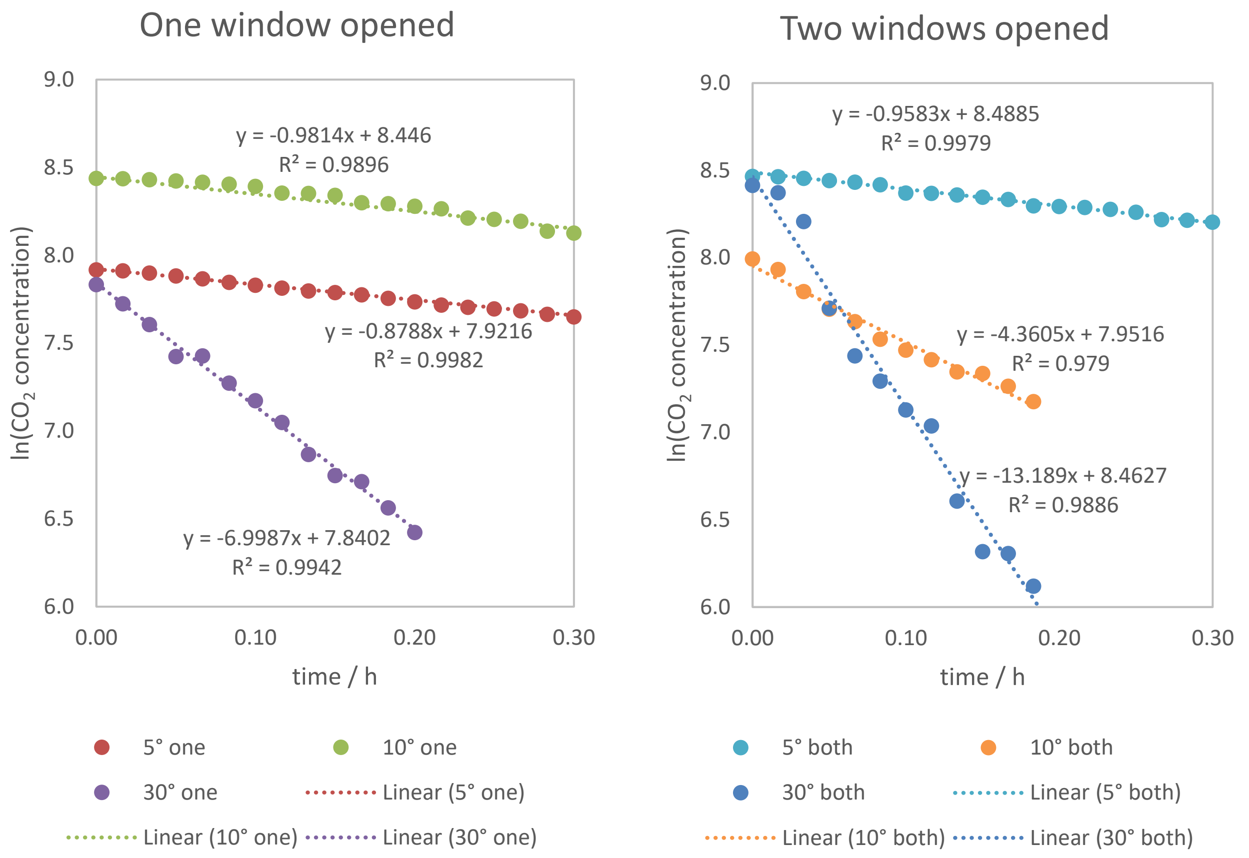


Figure 15. Natural logarithm of CO_2 concentration corrected for outside concentration plotted against time in hours with trendline whose declination represents air exchange rate for each case, without accounting for the infiltration rate of the room.

When comparing the measurements with equivalent simulation values (Figure 16 and Table 5), it seems that Flovent underestimates the flow at larger angles from the existing data, while at smaller angles it varies more. However, even though the measurements were performed at fairly low wind conditions, the impact of even a small amount of wind is likely to be much larger at high angles than at low angles, and the presence of wind can increase the air flow results significantly as seen in 3.1.1.5. It should additionally be kept in mind that the low angle flow from the simulation has been shown to be rather unreliable due to insufficient detail of the window frames in the model. Other impacts on the comparability between measurement and simulation results could be the existence of furniture in the room not being present in the simulation, the uncontrolled outdoor environment, the temperature not remaining constant in the room thereby affecting the calculations and possibly insufficient mixing of the CO_2 in the air before the measurement is started. The latter could explain the irregularities in the 30° cross-ventilation result (Figure 15) as it is more likely to affect the measurements done over a shorter time period due to the high air exchange. For more representative results and better comparability, the measurements should be repeated several times for each angle under varying conditions so that an average can be formed to compare against the simulation results. In general, the simulation results are in a similar order of magnitude and with better verification, the simulation model could likely be tweaked for better accuracy.

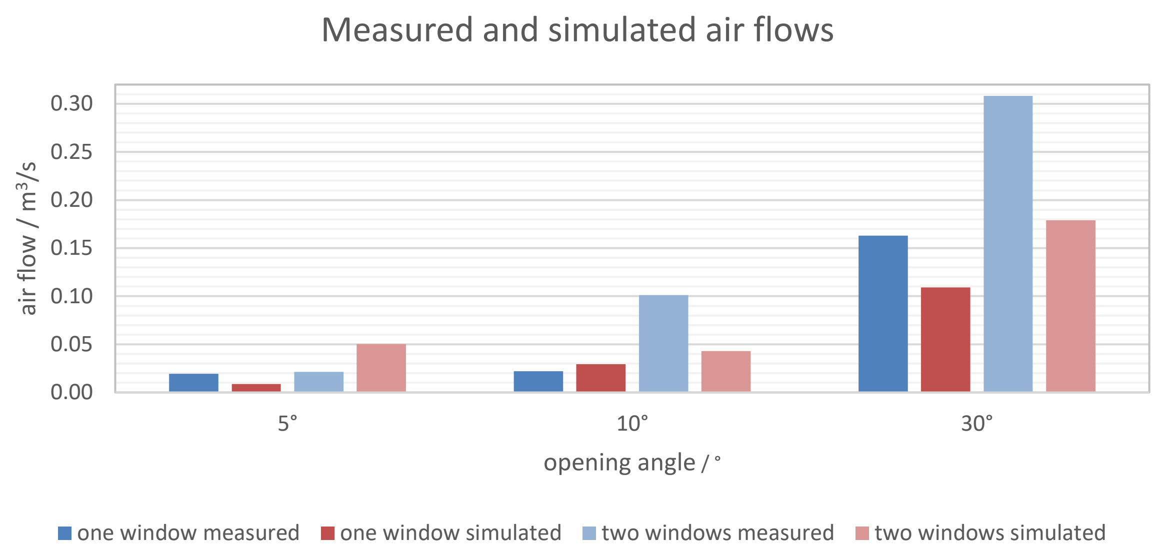


Figure 16. Comparison between measured and simulated air flows for all measured cases.

Table 5. Numerical comparison between measured and simulated air flows and exchange rates for all measured cases.

			measured		simulated	
	angle	**dT/K**	**q / (m³/s)**	**n / (1/h)**	**q / (m³/s)**	**n / (1/h)**
one window opened	5°	16.3	0.0195	0.8307	0.0086	0.3666
	10°	16.9	0.0219	0.9333	0.0294	1.2537
	30°	15.5	0.1630	6.9506	0.1091	4.6536
two windows opened	5°	14.9	0.0213	0.9102	0.0501	2.1381
	10°	13.2	0.1011	4.3124	0.0431	1.8393
	30°	13.8	0.3082	13.1409	0.1789	7.6281

3.2 User behaviour patterns

The four chosen data set exhibit very different behaviour patterns based on not only the user but also the room type. H1 and L1 are both bedrooms, but while H1 seems to open the window mostly during summer (Figure 17), keeping it open for long periods of time, L1 displays a regular opening behaviour throughout the monitored time (Figure 19). A common aspect for both of them are the angles being relatively low, with H1 showing some peaks at around 5°, 8°, 12° and 16°, while L1 looks to be constantly opened around 10° with inaccuracies stemming from the sensors. The bathroom (H2) and kitchen (L2) windows both show more frequent openings in the warm season with occasional openings in the heating season (Figure 18 and Figure 20). Here, the angle varies between being rather low (10° - 20°) and relatively high (varying around 100° which would be fully opened). H2 additionally shows a strong peak at around 50°.

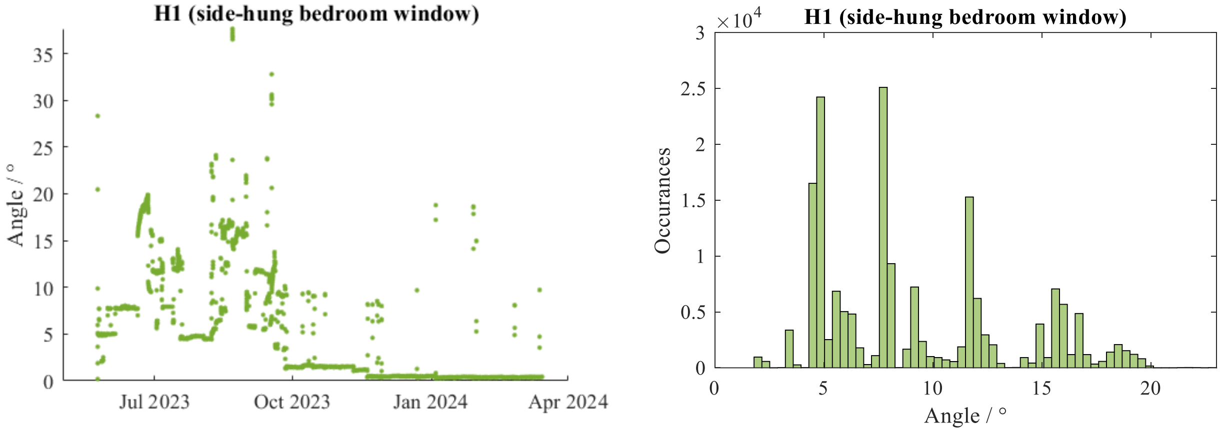


Figure 17. Angle distribution across the measured period (left) and angle occurrences without near-zero values (right) of H1 data set.

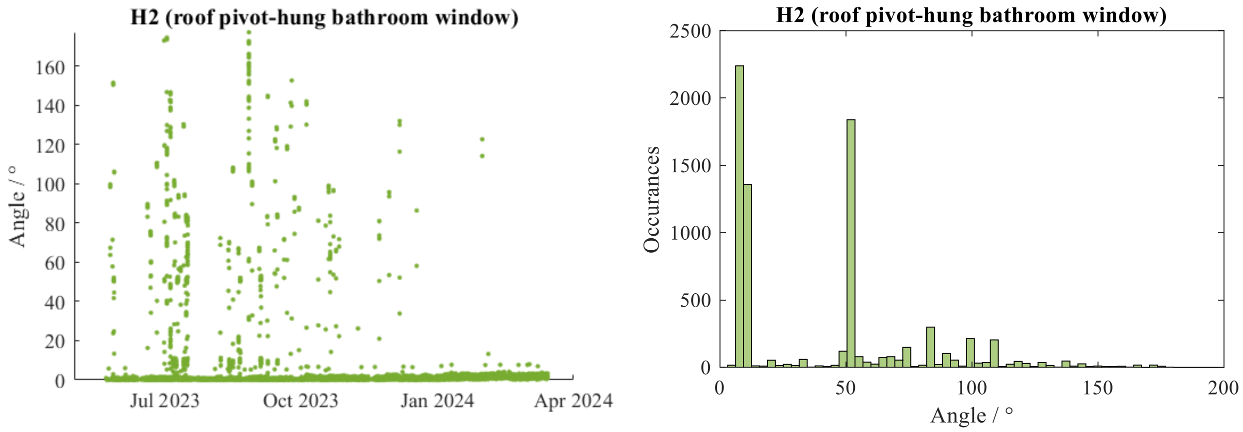


Figure 18. Angle distribution across the measured period (left) and angle occurrences without near-zero values (right) of H2 data set.

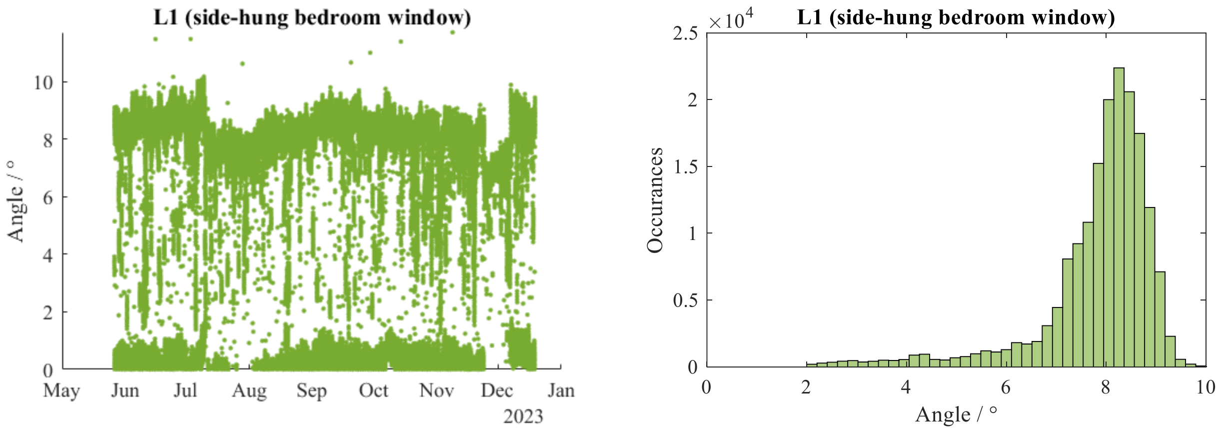


Figure 19. Angle distribution across the measured period (left) and angle occurrences without near-zero values (right) of L1 data set.

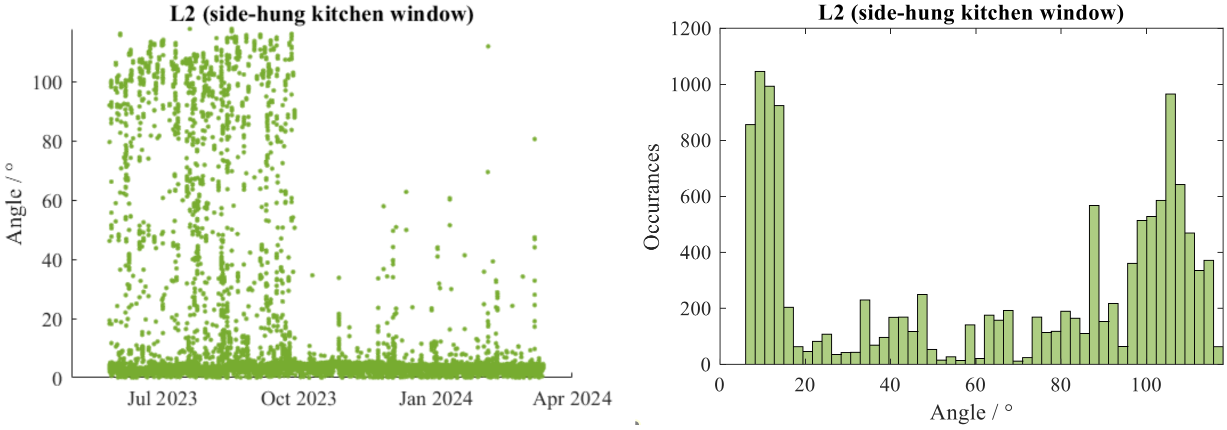


Figure 20. Angle distribution across the measured period (left) and angle occurrences without near-zero values (right) of L2 data set.

When plotting the opening angle against the time of day, only H2 and L2 show a clear pattern of being mostly opened between 6 am and 22 pm, with L2 also showing some continuous opening over several days at low angles (Figure 21). It is likely that these occur during the summer. H1 seems to be kept open for a longer time period more often, and the airing for L1 does not occur repeatedly at a specific time of day.

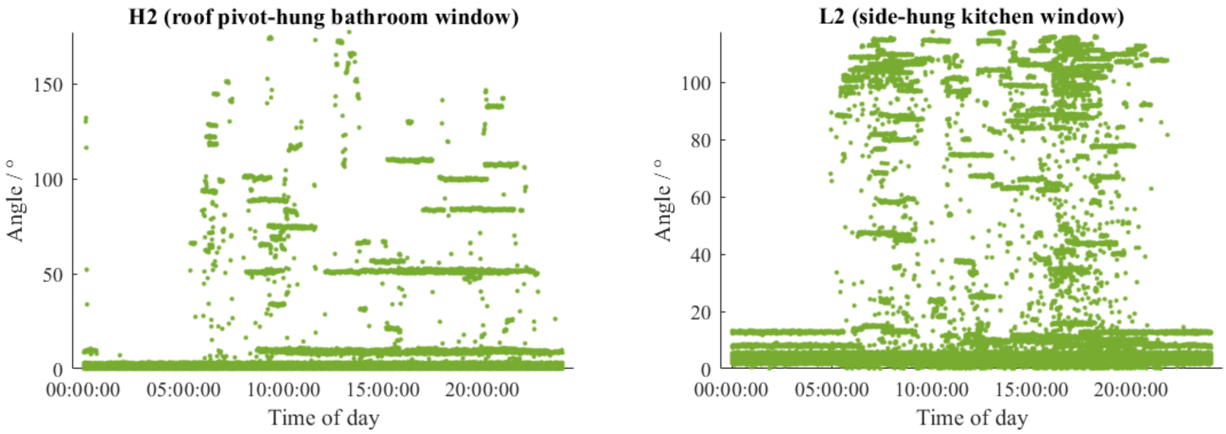


Figure 21. Daily distribution of angles for H2 (left) and L2 (right).

There does seem to be a correlation between higher indoor and outdoor temperatures and higher opening angles at least for H1 (Figure 22), since this window is mostly opened in the summer and then kept open continuously. It seems that the air flow is then adjusted not by short instances of wide openings, but by adjusting the angle on a smaller scale while keeping the window open. Other windows do not exhibit this behaviour, although H2 and L2 do show less frequent openings at colder outdoor temperatures (Figure 23). All windows also show less openings when indoor temperature falls below 20 °C, although a cause for that might be that the house or room is not occupied on those occasions. L1, with its regular openings, shows a reduction in openings below 0 °C (Figure 24), although it might just appear this way since these low temperatures are a less frequent occurrence in this climate.

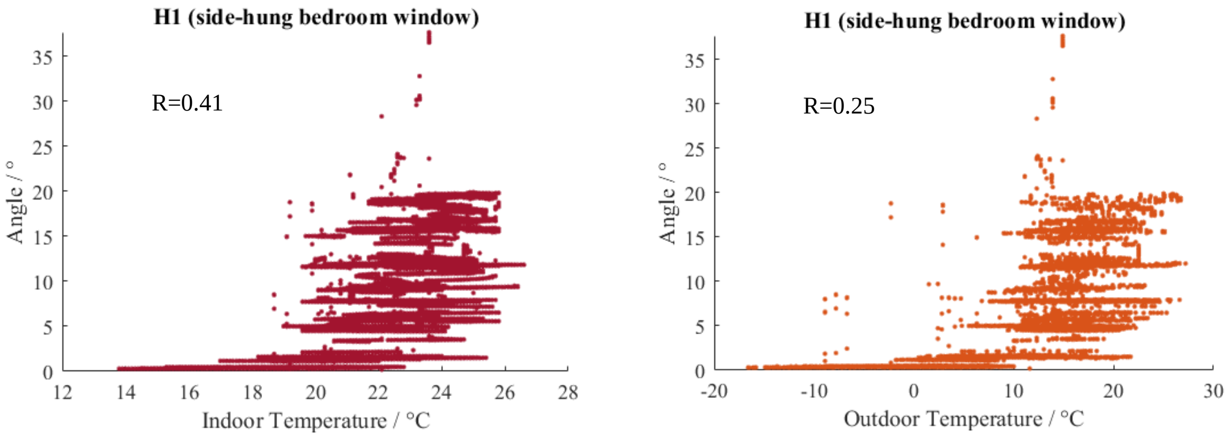


Figure 22. Correlation between indoor (left) and outdoor (right) temperatures and opening angle for H1. The correlation coefficients are 0.41 for indoor and 0.25 for outdoor temperature.

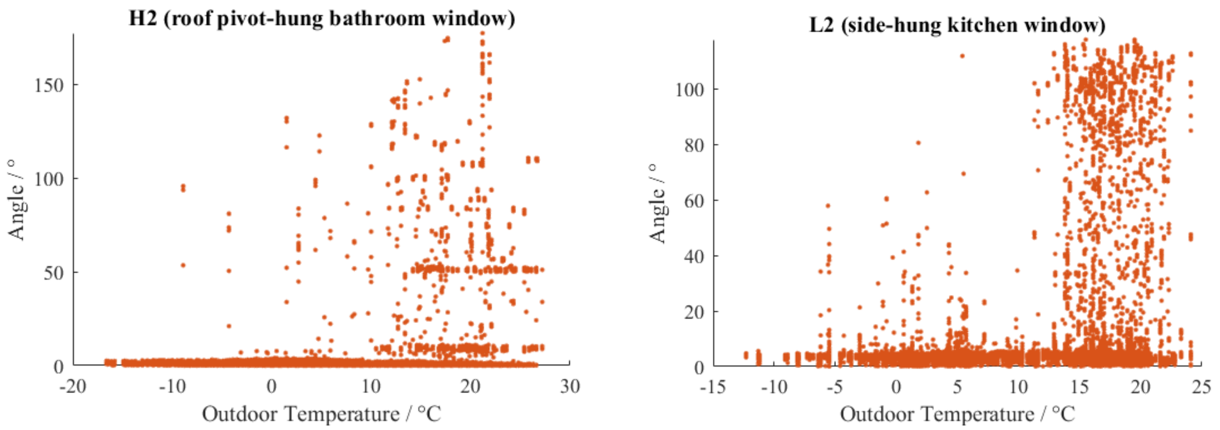


Figure 23. Correlation between outdoor temperature and opening angle for H2 (left) and L2 (right).

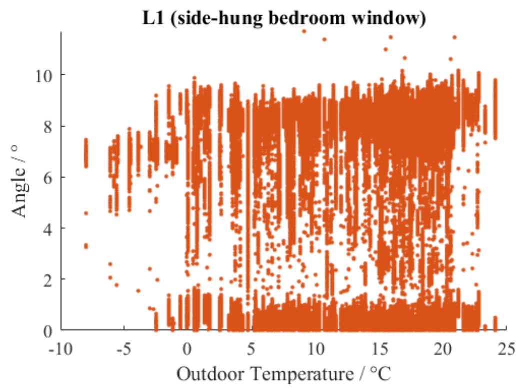


Figure 24. Correlation between outdoor temperature and opening angle for L1.

No clear correlation could be observed between opening angle and relative humidity or CO_2 concentration. However, a limiting factor when using those values alongside the indoor temperature is that the data might vary quite significantly across different rooms in the apartment due to different occupancy and usage. For example, bathroom and kitchen might more often have high humidity but if the sensor is not located in the same room its data would not reflect that.

In consequence of this limited data, the behaviour associated with window opening is very diverse and difficult to categorize as there are many reasons a window might be opened. For a more comprehensive analysis, more usable data is needed both for different room types and different user types from which several profiles could be created.

3.3 Heat loss by airing

3.3.1 Heat loss pattern across the year

The visualization of the airing heat loss in the parametric study is similar to a fairly typical distribution of heating demands in a heating-based climate, with higher losses during the colder season and lower losses during the warm season (Figure 25). When this is compared to the heating loss resulting from user schedules, only L1 is representative of this (Figure 26), while H2 and L2 partly exhibit the same pattern but with less frequent peaks during the colder months. H2 shows much higher heat losses during the summer due to its continuous opening behaviour. However, the heat losses in the summer might not be completely representative for all cases since heating is often turned off in that period altogether, especially when it is not controlled by a thermostat but the user themselves. In that case, even though the window opening does result in heat loss, this is not replenished by the heating system but possibly by solar gains or internal loads. Another aspect might be that the room is actually not used throughout the day, as could be the case for a bedroom, and the colder indoor temperature is actually desired. In these cases, it would be wrong to simply add the airing heat loss to the heating demand of a building.

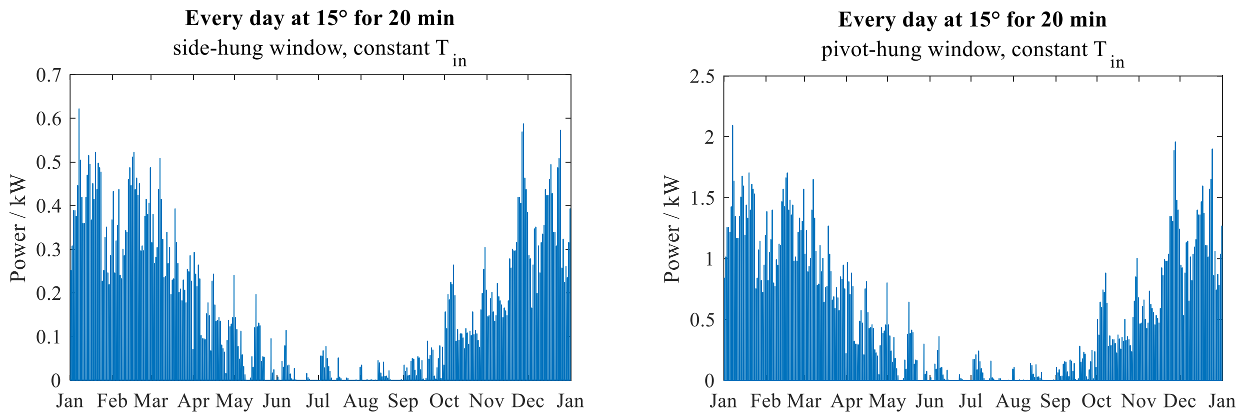
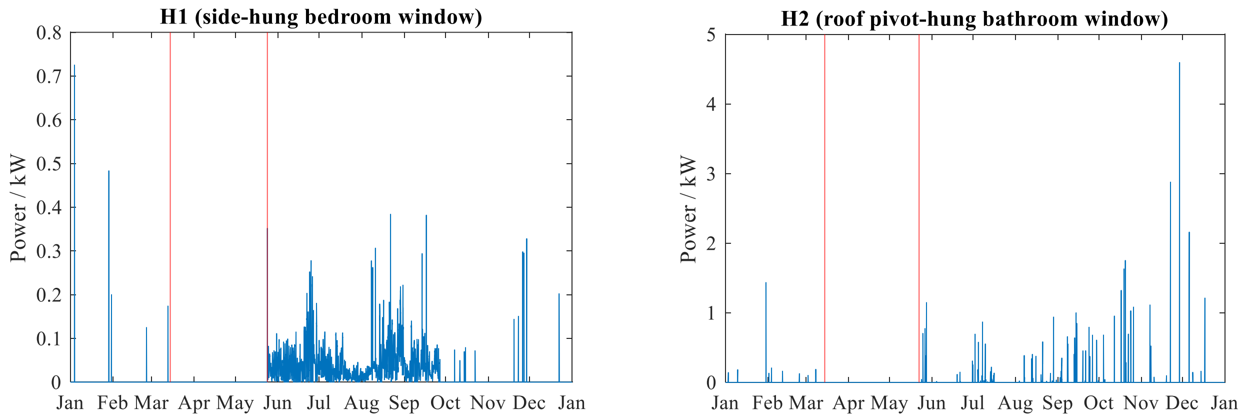


Figure 25. Yearly distribution of heat losses by airing for parametric study for Side-1 and Pivot-1.



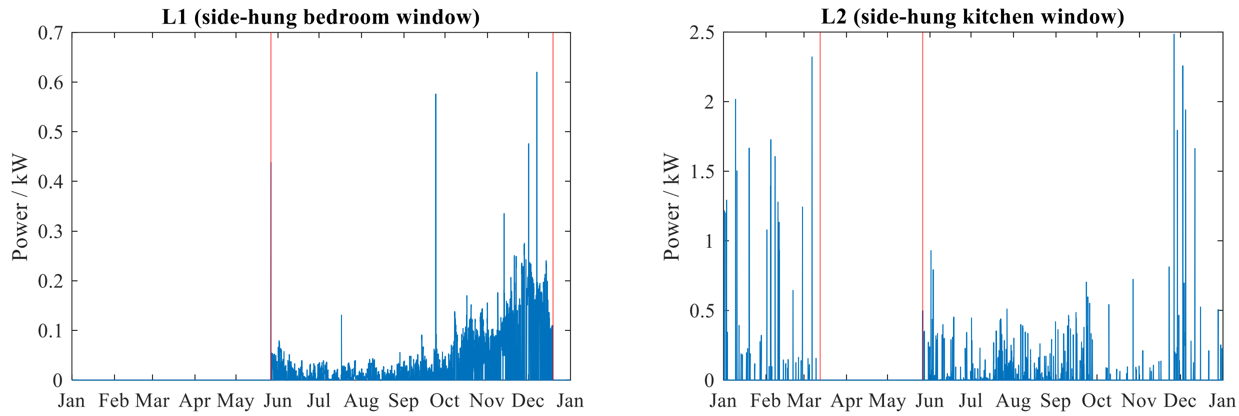


Figure 26. Yearly distribution of heat losses by airing for angle data sets H1, H2, L1 and L2 using airflow data from side-hung windows. The red lines represent the start and end times of measurements to show how much data is missing.

3.3.2 Sum of heat loss

When looking at the total heat loss across the year, the angle data sets show a lot of variation, and there is also a difference between using the air flow data from the room with side-hung windows and the room with pivot-hung windows (Figure 27). For the side hung data, the recommendation of 4 kWh/m^2 is exceeded for the two bedroom data sets, from which H1 expressed continuous opening in the summer and L1 regular opening behaviour throughout the year. The bathroom and kitchen windows from H2 and L2 are opened more intermittently so the total heat loss is lower than the recommended value. On the other hand, due to the higher airflows, the pivot-hung data result in a much higher heat loss for the bedroom windows compared to the recommendation, while the bathroom window has lower results and the kitchen window is only slightly lower than the recommendation for added heat loss. Obviously these observations are limited to the data that was collected and simulated and do not correspond to the actual room and window sizes from the apartments where the angle sensors were located. However, it does underline the variety of opening behaviour and also shows the influence of the window size which could be very different even in similar sized rooms. This can be seen in the parametric results as well as comparison of the results for the same opening scenario for side- and pivot-hung data to the recommended values (Figure 28). The heat loss is about half of the corresponding recommended value for the side-hung window, while it is a little higher than the recommended value for the pivot-hung window. The implication of this is that it does not suffice to look at the angle alone when investigating user behaviour, but also the size, type and possibly location of windows. It is also not unlikely that opening behaviour is in fact directly influenced by its resulting air flow, at least in cases where a specific air exchange or heat loss is desired, which makes the analysis even more complicated.

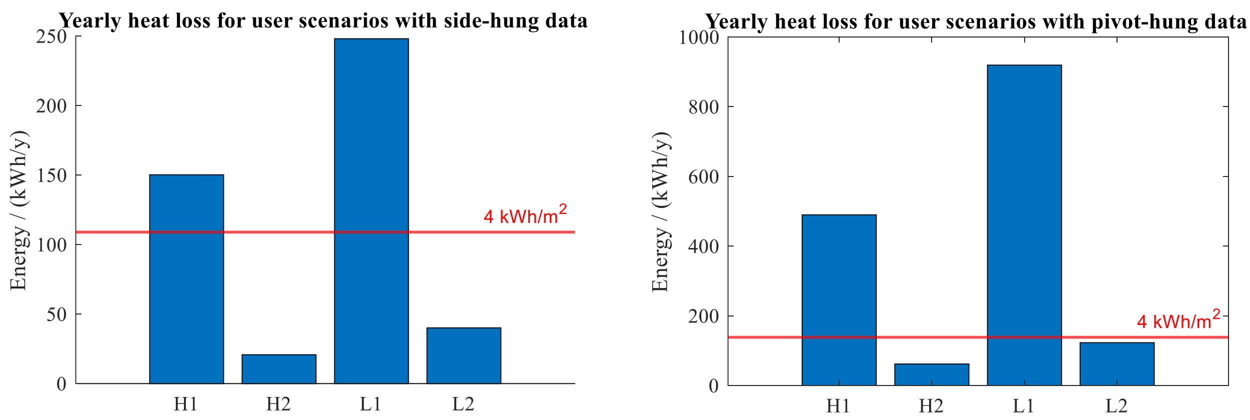


Figure 27. Total heat loss of each user scenario (Figures 17 to 20) for side- and pivot-hung data, upscaled to a whole year by average of existing data. The red line represents the recommendation of 4 kWh/m^2.

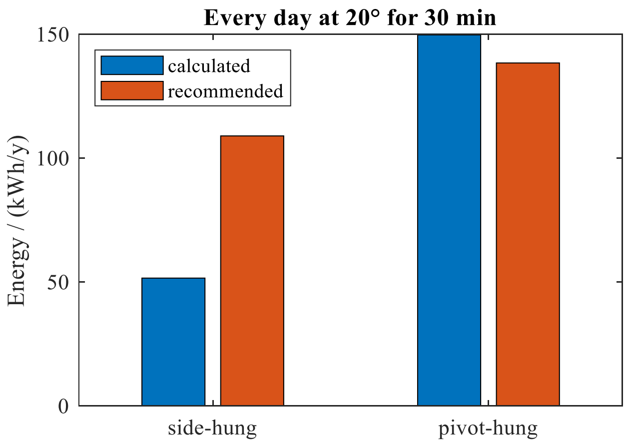


Figure 28. Total yearly heat loss for one specific scenario and side-/ pivot-hung data, the red bars represent the corresponding recommendation of 4 kWh/m².

3.3.3 Influence of duration and angle

The influence of duration is here shown to be linear (Figure 29), which is a direct result of the transient simulation results being upscaled to fit the time window of a complete year. In reality, this might not be the case as the longer opening durations could result in a decrease of indoor temperature, which in turn will reduce the air flow over time as the temperature difference decreases. The extent to which this happens will depend on the output and settings of the heating system, but it will most likely be the case for the higher opening angles with high air flows, as the heating system will struggle to compensate for the lost heat. On the other hand, according to the user data, high opening angles over a longer period of time most often occur during summer when the window is used for cooling and a large amount of heat loss is desired, so these extreme scenarios are potentially unrealistic.

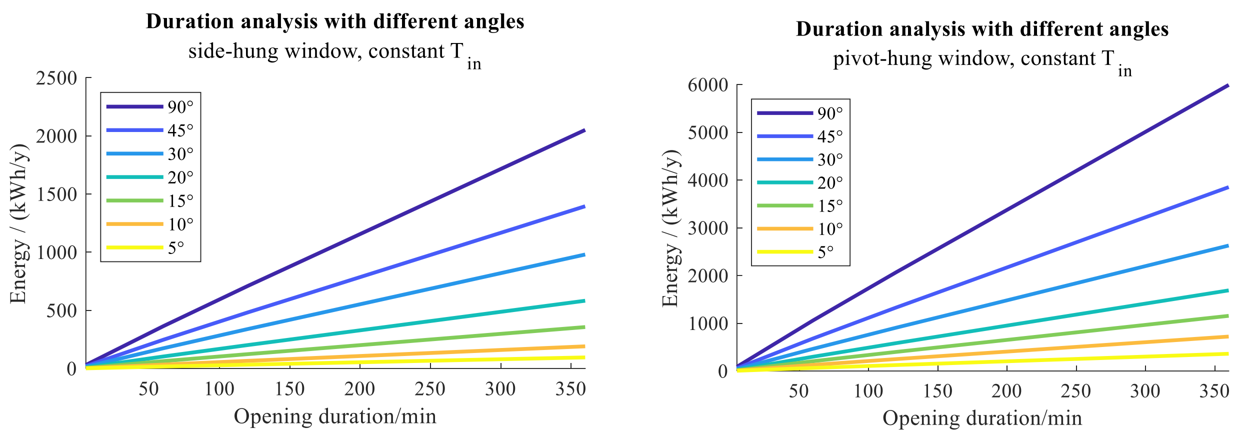


Figure 29. Total yearly heat loss plotted against duration for different angles, for side- and pivot-hung data (start time of 00:00 and frequency of 1).

In comparison, the energy curves by angle (Figure 30) strongly resemble the air flow curves in 3.1.1 as the heat loss calculation is largely based on that data.

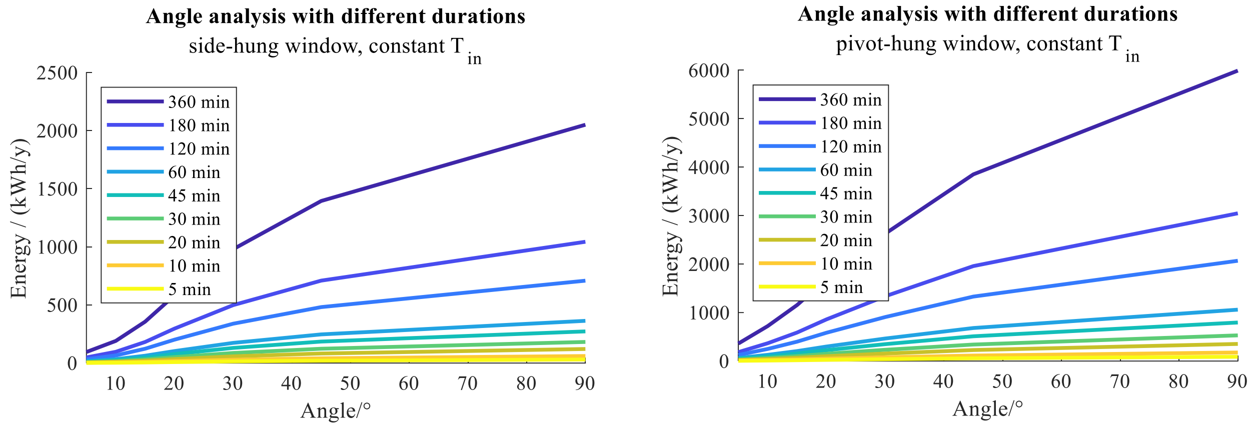


Figure 30. Total yearly heat loss plotted against angle for different durations, for side- and pivot-hung data (start time of 00:00 and frequency of 1).

When comparing different angle and duration scenarios with the results from user data and recommended values for airing heat loss, the total heat loss with side-hung data from a 10° opened window for 200 min approximately corresponds to a 75° opened window for 20 min, which both come close to the recommended value of 4 kWh/m_2 (Figure 31). For pivot-hung data, a 60° opened window for 10 minutes and a 10° opened window for 60 min fall together with the recommendation (Figure 32).

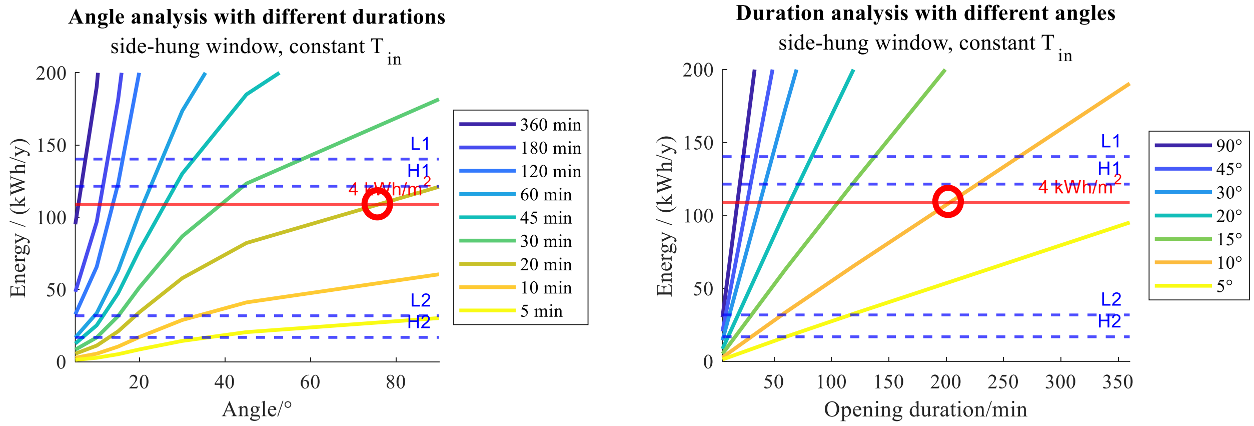


Figure 31. Total yearly heat loss plotted against angle (left) and duration (right) with recommended value in red and user scenarios in blue, for side-hung data.

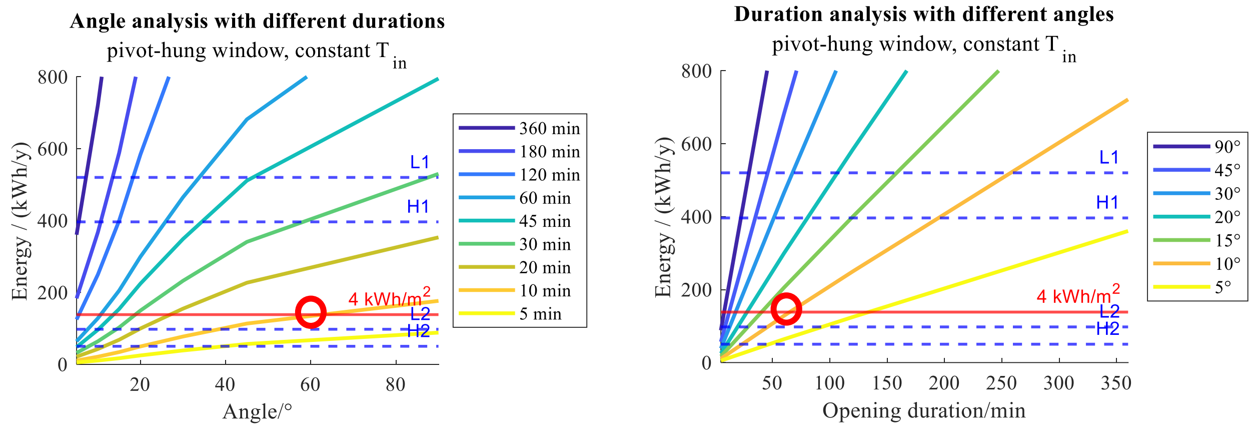


Figure 32. Total yearly heat loss plotted against angle (left) and duration (right) with recommended value in red and user scenarios in blue, for pivot-hung data.

3.3.4 Influence of indoor temperature and start time of opening

The influence of an assumed lower indoor temperature at night when airing during the night hours is shown in Figure 33. As should be expected, the colder nighttime temperature decreases the total heat loss when considering night-time openings, for the pivot-hung window even quite significantly, but obviously this only works when the heating setpoints are actually set lower. In a realistic scenario, the amount of this reduction is probably not representative as there will be a mixture of opening the window at night and during the day, depending on the type of room, the user and the season.

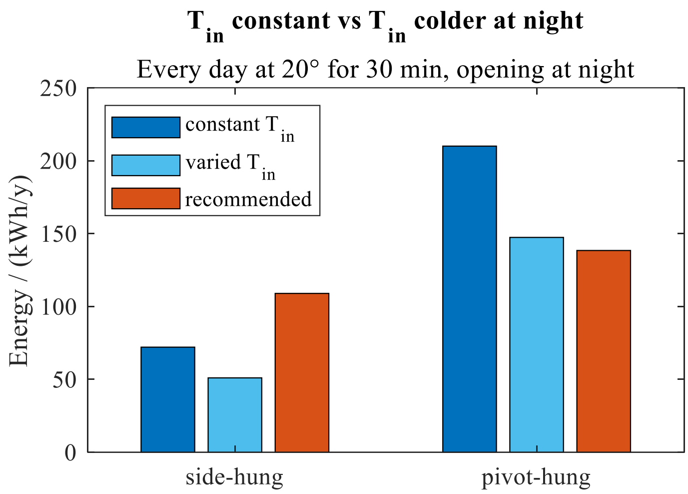


Figure 33. Total yearly heat loss for constant indoor temperature of 21 °C (dark blue), indoor temperature that is lowered to 18 °C at night (light blue) and the recommendation by BBR.

The difference between the two indoor temperature scenarios also becomes visible when analysing the impact of start time of the opening, as it only has an effect on the results for the scenarios with a 00:00 start time for opening the window (Figure 34 and Figure 35). When looking at the constant indoor temperature scenarios, the assessment with the impact of the duration and a constant 20° angle shows a sinus-like pattern which resembles the pattern of outdoor temperatures during the day, as a lower outdoor temperature results in a larger temperature difference and a higher heat loss (Figure 35). Compared to that, the impact of the angles with a constant duration of 20 minutes shows nearly no difference between 12:00 and 18:00 but higher results at 00:00 and 06:00 (Figure 34). It is possible that the pattern is less visible as this data, being limited to 30 minutes duration, does not include the more extreme scenarios with the long durations that result in significantly higher heat losses. This leads to the possible conclusion that the time during the day is of less importance when considering more realistic opening behaviour.

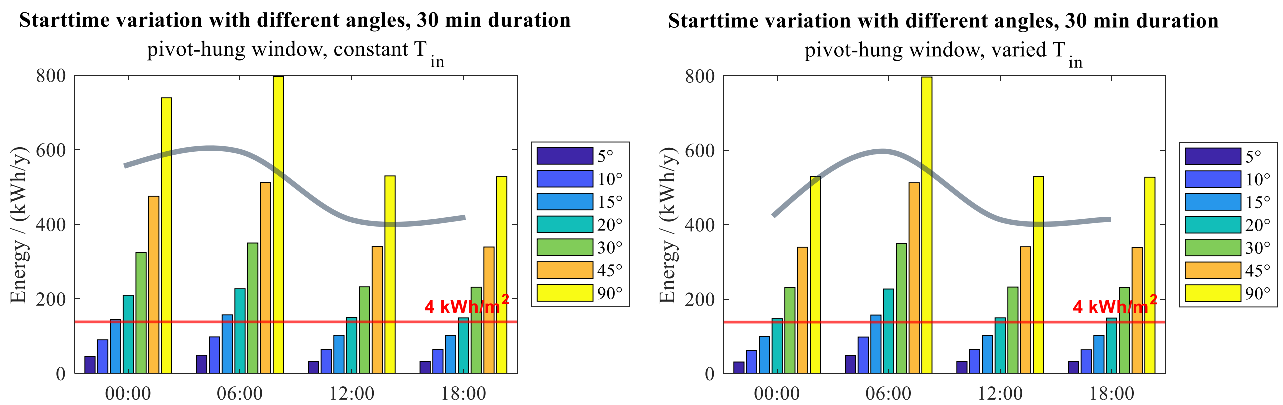


Figure 34. Difference in total yearly heat loss for different start times of window opening with different angles and the two indoor temperature scenarios (left vs right).

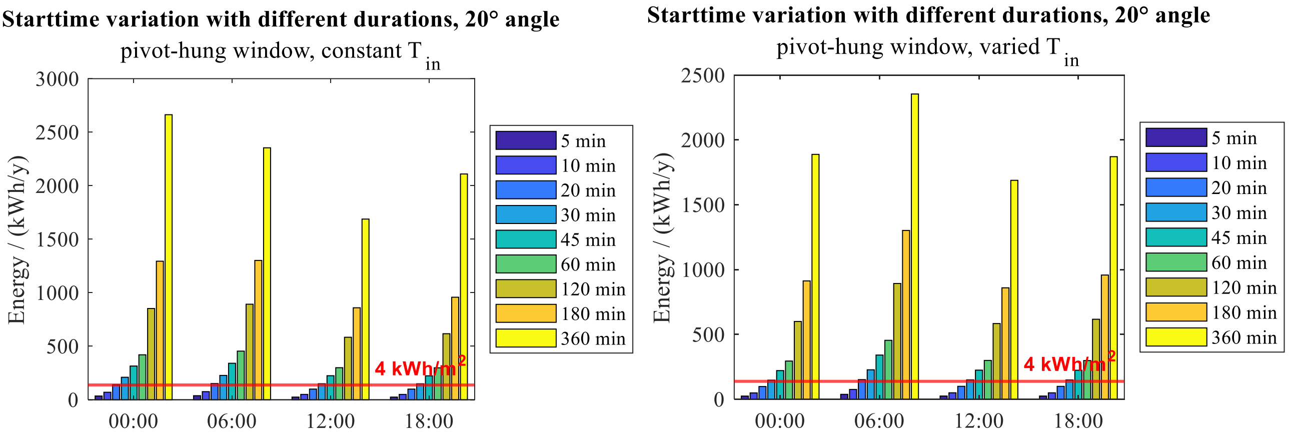


Figure 35. Difference in total yearly heat loss for different start times of window opening with different durations and the two indoor temperature scenarios (left vs right).

3.3.5 Influence of frequency

The impact of frequency of window opening, here defined as the number of days passed between the opening instances, is shown to be non-linear (Figure 36). It can also be observed that when the frequency of window opening is down to 7 (once per week), the results for all but the most extreme scenarios remain below the recommended value of 4 kWh/m².

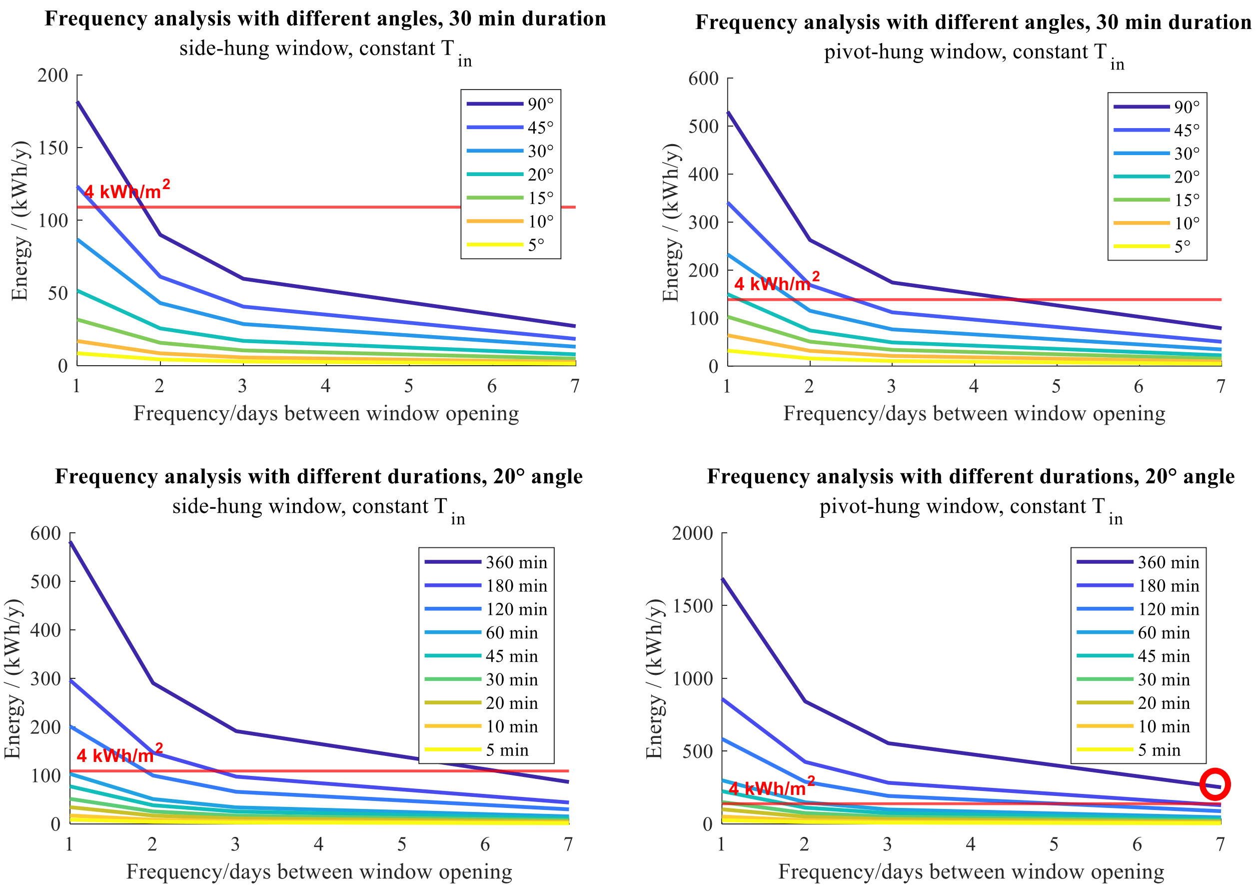


Figure 36. Total yearly heat loss plotted against frequency for different angles and durations for side- and pivot-hung data.

3.3.6 Impact of different parameters

Figure 37 shows the impact that the different parameters have on the airing heat loss represented by the factor by which the lowest case is increased to get the highest case. It is apparent that the opening duration has the largest impact followed by opening angle, while opening frequency and window type and size have a lower impact, although still affecting the results by a factor of around 3 and 7 respectively. The variation of the indoor temperature profile and time of opening increases the results by a factor of roughly 1.5 from the lowest to the highest case. However, when looking at these impacts, it is important to consider the range that was used in the parameters and chosen slightly arbitrarily. The highest opening duration in the parametric study is 6 hours, which will probably lie outside a realistic range when considering daily window opening, and another value could easily be chosen which would significantly change the impact when compared to the lowest duration of 5 minutes. Setting the maximum duration to 2 hours, for example, sets the duration impact to a similar value as varying the opening angle between 5° and 90°. Similarly, lower and higher values could be chosen for the frequency parameters as there are no natural limits as is the case for opening angles and start time of opening. For the latter, the impact is likely a bit higher as the four chosen times might not represent the actual lowest and highest heat losses. Based on outdoor temperatures, they are likely to occur in the early morning hours and afternoon. While little variation is to be expected in the indoor temperature profile, only two alternatives were investigated. Likewise, only two window types with their respective sizes were analyzed, while larger or smaller windows certainly are possible and would increase the perceived impact. Nevertheless, based on the reasonability in the range of parameters, the observation can be made that opening angle and duration along with frequency and window size do impact the airing heat loss significantly.

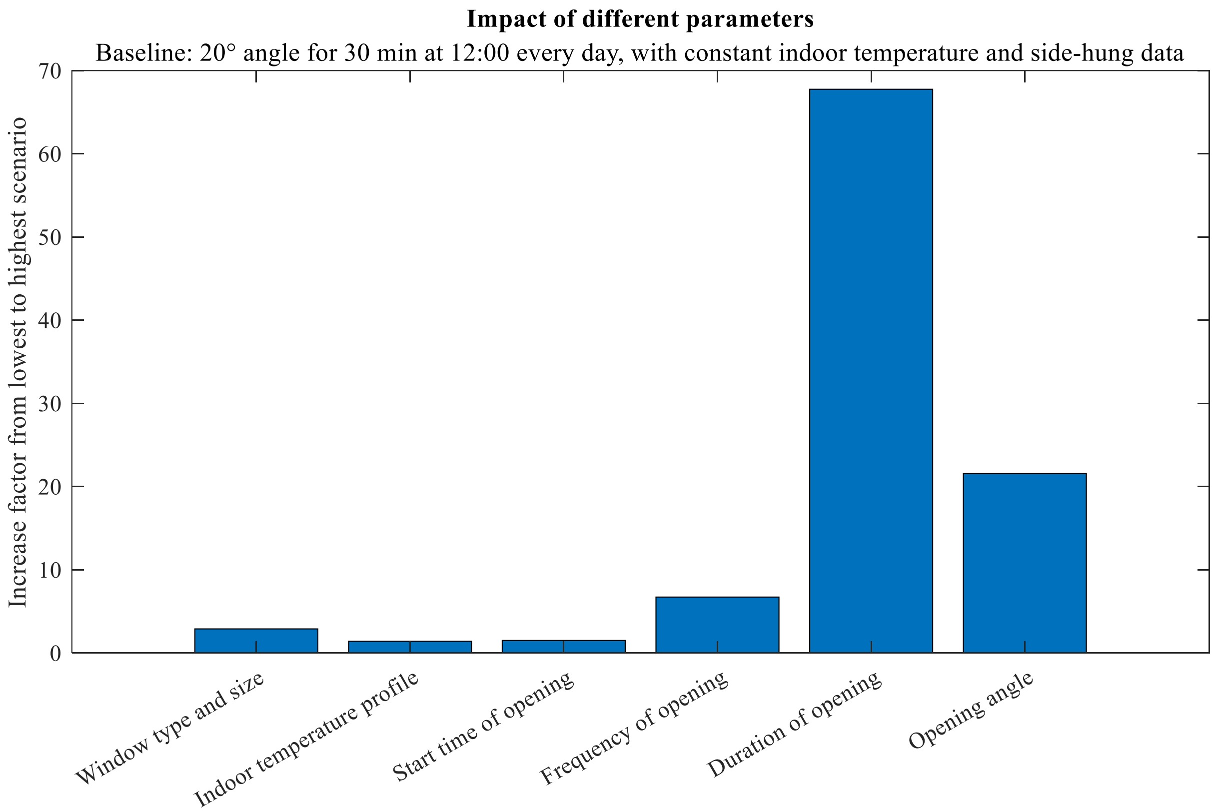


Figure 37. Impact of parameters shown as the increase factor from the lowest to the highest case in terms of energy results.

3.3.7 Limitations with crossflow and wind

Neither the user angle data nor the parametric studies were tested with simulated air flows where wind was added as a parameter, since no comprehensive study was done with changing wind parameters. However, as seen in 3.1.1.5, the addition of wind can significantly increase the air flow by several magnitudes. Therefore, a more comprehensive study should take this into account also when analysing user behaviour, since the possibility of cross-ventilation was not investigated in this thesis due to lacking data.

4 Conclusions

Looking at the results, it is difficult to draw any singular conclusion, as airing heat loss is dependent on many different parameters. The comparison between side-hung and pivot-hung windows suggests that the latter allows for a more efficient air exchange, however the results are inconclusive due to the lack of comparability of the window sizes. The air flow simulation results were verified to be in a similar order of magnitude, but a more comprehensive series of measurements is needed to determine the reliability of Flovent air flows. Generally, CFD simulations offer many possibilities in measuring airflow scenarios compared to the effort of real-life measurements, and with the verification combined with some tweaks, particularly regarding the detail of the window frames, they could be an accurate tool to perform these analyses.

The analysis of window opening behaviour was not sufficiently representative due to limited usability of collected data. While some minimal correlations could be identified between opening angle and outdoor and indoor temperatures, none were found for other environmental parameters even though other studies have found connections (Andersen et al., 2013). More detailed logging of parameters for individual rooms could shed more light on this.

The parametric and user data results for yearly heat loss can match the Boverket recommendation for airing heat loss, but depending on scenario can also be very far off. It seems that angle, duration and frequency of window opening, along with window size all affect the results significantly, while the time of day of the opening and different indoor temperature profiles had a lesser impact. As most of these are part of the collected user data, a broader study with more reliable data could further illuminate behaviour patterns where different profiles could be created for different use cases. However, the size of the window should be integrated into further processing of this data, as the angle and time of opening alone seem insufficient. Also, investigating the possibility of cross-ventilation within the user profiles could be a useful addition paired with wind speed data, as the simulation results have shown that air flow can increase manyfold under certain conditions. Additionally, a more holistic approach with a complete energy simulation could illustrate the relevance of the found heat losses, as they do not necessarily result in a higher heating demand especially during the summer when heat lost at night can be recovered by solar gains.

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Appendix A

Input tables for interpolation and heat loss calculation

Side-hung data

inflow	30 K	20 K	15 K	10 K	5 K	0 K
0°	0	0	0	0	0	0
10°	0.013344	0.01058	0.009587	0.007386	0.005048	0
15°	0.025967	0.020998	0.016421	0.013086	0.009239	0
20°	0.038023	0.030687	0.026215	0.021346	0.015352	0
30°	0.061848	0.049689	0.042585	0.034626	0.024716	0
45°	0.086594	0.070584	0.06112	0.049593	0.034814	0
90°	0.129977	0.105208	0.086763	0.070133	0.049298	0

outflow	30 K	20 K	15 K	10 K	5 K	0 K
0°	0	0	0	0	0	0
10°	0.008809	0.007519	0.006614	0.005116	0.003407	0
15°	0.018707	0.016085	0.011494	0.009209	0.006512	0
20°	0.028456	0.027017	0.021038	0.017042	0.012335	0
30°	0.061405	0.047504	0.036757	0.029825	0.021452	0
45°	0.07325	0.063265	0.054967	0.044626	0.031294	0
90°	0.120503	0.097385	0.080722	0.065204	0.04553	0

Pivot-hung data

inflow	30 K	20 K	15 K	10 K	5 K	0 K
0°	0	0	0	0	0	0
10°	0.048765	0.037386	0.029392	0.021539	0.014953	0
15°	0.079682	0.059324	0.046853	0.035308	0.024467	0
20°	0.107563	0.084216	0.06945	0.0538	0.037509	0
30°	0.15667	0.126685	0.10913	0.088676	0.06239	0
45°	0.22924	0.18518	0.1597	0.130425	0.093034	0
90°	0.35524	0.286712	0.248325	0.204235	0.146555	0

outflow	30 K	20 K	15 K	10 K	5 K	0 K
0	0	0	0	0	0	0
10	0.049056	0.037636	0.029409	0.021413	0.014672	0
15	0.079976	0.059581	0.047044	0.035289	0.024298	0
20	0.10753	0.084356	0.069659	0.053902	0.037573	0
30	0.15663	0.12643	0.109135	0.088807	0.062254	0
45	0.22925	0.185015	0.159535	0.130585	0.092954	0
90	0.355116	0.286669	0.248402	0.204367	0.146423	0

Appendix B

Matlab code

Creating schedules

```
%clear all
clc
close all

%generate timedata in minutes for 1 year
t1 = datetime(2023,1,1,0,0,0);
t2 = datetime(2023,12,31,23,59,0);
time = t1:minutes(5):t2;

starttime=[0 6 12 18];
frequency=[1 2 3 7]; %daily, every 2nd, 3rd day, weekly
duration=[5 10 20 30 45 60 120 180 360];
angle=[5 10 15 20 30 45 90];

tic;

for i=1:length(starttime)
    for j=1:length(frequency)
        for k=1:length(duration)
            for l=1:length(angle)
                all_angles{i, j, k, l}=getangle(time,starttime(i), duration(k),
angle(l), frequency(j));
            end
        end
    end
end

elapsed_time = toc;
disp(['Elapsed time: ' num2str(elapsed_time) ' seconds']);

%%

function angle = getangle(t, st, d, a, f)
    start_datetime = datetime(year(t), month(t), day(t), 0, 0, 0) + hours(st);
    end_datetime = start_datetime + minutes(d);

    % Check if t is between start_datetime and end_datetime (open on the right)
    is_between = isbetween(t, start_datetime, end_datetime, 'openright');
    divisible=mod(day(t, 'dayofyear'),f)==0;
    angle = a .*is_between .*divisible;
end
```

Calculating heat loss

```
%clear all
clc
close all

%get airflow data
anglevalues = [0; 10; 15; 20; 30; 45; 90];
Tvalues = [30 20 15 10 5 0];
valuesout_sd=table2array(sd_out);
valuesin_sd=table2array(sd_in);
valuesout_pv=table2array(pv_out);
```

```
valuesin_pv=table2array(pv_in);

starttime=[0 6 12 18];
frequency=[1 2 3 7]; %daily, every 2nd, 3rd day, weekly
duration=[5 10 20 30 45 60 120 180 360];
angle=[5 10 15 20 30 45 90];

%%
%go through all scenarios
tic
%preallocating
all_heatsum_sd = cell(length(starttime), length(frequency), length(duration),
length(angle));
all_heat_sd = cell(length(starttime), length(frequency), length(duration),
length(angle));
all_heatsum1_sd = cell(length(starttime), length(frequency), length(duration),
length(angle));
all_heat1_sd = cell(length(starttime), length(frequency), length(duration),
length(angle));

all_heatsum_pv = cell(length(starttime), length(frequency), length(duration),
length(angle));
all_heat_pv = cell(length(starttime), length(frequency), length(duration),
length(angle));
all_heatsum1_pv = cell(length(starttime), length(frequency), length(duration),
length(angle));
all_heat1_pv = cell(length(starttime), length(frequency), length(duration),
length(angle));

for i=1:length(starttime)
    for j=1:length(frequency)
        for k=1:length(duration)
            for l=1:length(angle)
                [all_heatsum_sd{i,j,k,l}, all_heat_sd{i,j,k,l}]=getheat(Tin, Tout,
Tvalues, anglevalues, valuesin_sd, valuesout_sd, all_angles{i,j,k,l}, 5);
                [all_heatsum1_sd{i,j,k,l}, all_heat1_sd{i,j,k,l}]=getheat(Tin1, Tout,
Tvalues, anglevalues, valuesin_sd, valuesout_sd, all_angles{i,j,k,l}, 5);
                [all_heatsum_pv{i,j,k,l}, all_heat_pv{i,j,k,l}]=getheat(Tin, Tout,
Tvalues, anglevalues, valuesin_pv, valuesout_pv, all_angles{i,j,k,l}, 5);
                [all_heatsum1_pv{i,j,k,l}, all_heat1_pv{i,j,k,l}]=getheat(Tin1, Tout,
Tvalues, anglevalues, valuesin_pv, valuesout_pv, all_angles{i,j,k,l}, 5);
            end
        end
    end
end

elapsed_time = toc;
disp(['Elapsed time: ' num2str(elapsed_time) ' seconds']);
%%
%go through user data

[heatsum_h1_sd, heat_h1_sd]=getheat(Tin_H, Tout_H, Tvalues, anglevalues, valuesin_sd,
valuesout_sd, h1, 1);
[heatsum_h2_sd, heat_h2_sd]=getheat(Tin_H, Tout_H, Tvalues, anglevalues, valuesin_sd,
valuesout_sd, h2, 1);
[heatsum_l1_sd, heat_l1_sd]=getheat(Tin_L, Tout_L, Tvalues, anglevalues, valuesin_sd,
valuesout_sd, l1, 1);
[heatsum_l2_sd, heat_l2_sd]=getheat(Tin_L, Tout_L, Tvalues, anglevalues, valuesin_sd,
valuesout_sd, l2, 1);

[heatsum_h1_pv, heat_h1_pv]=getheat(Tin_H, Tout_H, Tvalues, anglevalues, valuesin_pv,
valuesout_pv, h1, 1);
```

```
[heatsum_h2_pv, heat_h2_pv]=getheat(Tin_H, Tout_H, Tvalues, anglevalues, valuesin_pv,
valuesout_pv, h2, 1);
[heatsum_l1_pv, heat_l1_pv]=getheat(Tin_L, Tout_L, Tvalues, anglevalues, valuesin_pv,
valuesout_pv, l1, 1);
[heatsum_l2_pv, heat_l2_pv]=getheat(Tin_L, Tout_L, Tvalues, anglevalues, valuesin_pv,
valuesout_pv, l2, 1);

%%
function [heatsum,heat]=getheat(Tin, Tout, Tvalues, anglevalues, valueshigh, valueslow,
angle, minutenumber)


    % Check conditions
    idx = Tout < Tin & angle~=0;

    % Calculate temperature difference
    dT = min(Tin - Tout, 30);

    % Interpolate values based on temperature and angle
    airhigh = interp2(Tvalues, anglevalues, valueshigh, dT, angle);
    airlow = interp2(Tvalues, anglevalues, valueslow, dT, angle);

    airhigh(isnan(airhigh)) = 0;
    airlow(isnan(airlow)) = 0;

    % Air constants
    cp = 1006; % J/kgK, specific heat capacity air
    p = 100000; % Pa, equals 1 bar
    Rsp = 287.0500676; % J/kgK, specific gas constant dry air

    % Air density
    din = p ./ (Rsp .* (Tout + 273.15));
    dout = p ./ (Rsp .* (Tin + 273.15));

    % Calculate heat loss
    heatlow = cp * dout .* airlow .* dT ./1000;
    heathigh = cp * din .* airhigh .* dT ./1000;
    heat = ((heatlow + heathigh) / 2) .* (minutenumber/60) .* idx;

    heatsum = sum(heat);
end
```

Creating temperature profiles

```
%clear all
clc
close all

%Tout lund

t1 = datetime(2023,1,1,0,0,0);
t2 = datetime(2023,12,31,23,59,0);
time = t1:hours(1):t2;
time2=t1:minutes(5):t2;
Lundtt=timetable(time',table2array(Lundtmy));

Lundtt2=retime(Lundtt, time2, 'previous', 'TimeStep', minutes(5));

Tout=Lundtt2.Var1';

%%
```

```
Tin=21 * ones(1, 105120);

%%
%Tin colder at night

t1 = datetime(2023,1,1,0,0,0);
t2 = datetime(2023,12,31,23,59,0);
time = t1:minutes(5):t2;
temp=nan(1, length(time));
T = timetable(time',temp');

% Assign values based on time condition
T.Var1 = ones(height(T), 1) * 21; % Default value of 21
T.Var1(hour(T.Properties.RowTimes) >= 22 | hour(T.Properties.RowTimes) < 6) = 18; %
Assign 18 between 21:00 and 6:00

Tin1=T.Var1';
```

Analysing user data

```
%clear all
clc
close all

%raw data for graphs and comparison

hlog=retime(table2timetable(raw_hlog), 'minutely', 'nearest');
hout=retime(table2timetable(raw_hout), "minutely", "nearest");
h1tt=table2timetable(raw_h1);
h2tt=table2timetable(raw_h2);
raw_h=synchronize(hlog, hout, h1tt, h2tt, 'union');

llog=retime(table2timetable(raw_llog), 'minutely', 'nearest');
lout=retime(table2timetable(raw_lout), "minutely", "nearest");
l1=table2timetable(raw_l1);
l2=table2timetable(raw_l2);
raw_l=synchronize(llog, lout, l1, l2, 'union');

%%
%no of minutes
upscale_h1=525600/length(h1tt.Time);
upscale_h2=525600/length(h2tt.Time);
upscale_l1=525600/length(l1tt.time);
upscale_l2=525600/length(l2tt.time);

%%
%lund tmy as outdoor temp for calculation

t1 = datetime(2023,1,1,0,0,0);
t2 = datetime(2023,12,31,23,59,0);
time = t1:minutes(1):t2;
time1 = t1:hours(1):t2;
Lundtt=timetable(time1',table2array(Lundtmy));

Lundtt2=retime(Lundtt, time, 'previous', 'TimeStep', minutes(1));

Tout3=Lundtt2.Var1';
%%

%Hörby actual temp as outdoor temp for calculation
```

```
t1 = datetime(2023,1,1,0,0,0);
t2 = datetime(2023,12,31,23,59,0);
time = t1:minutes(1):t2;
Horbytt=table2timetable(sort_hout);

Horbytt2=retime(Horbytt, time, 'nearest', 'TimeStep', minutes(1));

Tout_H=Horbytt2.tempout';

%Lund actual temp as outdoor temp for calculation

t1 = datetime(2023,1,1,0,0,0);
t2 = datetime(2023,12,31,23,59,0);
time = t1:minutes(1):t2;
Lundtt=table2timetable(sort_lout);

Lundtt2=retime(Lundtt, time, 'nearest', 'TimeStep', minutes(1));

Tout_L=Lundtt2.tempout';

%prepare H data for calculation

hlog=table2timetable(sort_hlog);
h1tt=table2timetable(sort_h1);
h2tt=table2timetable(sort_h2);

h1tt2=retime(h1tt, time, 'TimeStep', minutes(1));
h2tt2=retime(h2tt, time, 'TimeStep', minutes(1));
hlogtt=retime(hlog, time, 'nearest', 'TimeStep', minutes(1));

Tin_H=hlogtt.temp';

h1=h1tt2.angle';
h1(h1<2)=0;
h1(h1>90)=90;
h2=h2tt2.angle';
h2(h2<5)=0;
h2(h2>90)=90;

%prepare L data for calculation

llog=table2timetable(sort_llog);
l1tt=table2timetable(sort_l1);
l2tt=table2timetable(sort_l2);

l1tt2=retime(l1tt, time, 'TimeStep', minutes(1));
l2tt2=retime(l2tt, time, 'TimeStep', minutes(1));
llogtt=retime(llog, time, 'nearest', 'TimeStep', minutes(1));

Tin_L=llogtt.temp';

l1=l1tt2.angle';
l1(l1<2)=0;
l1(l1>90)=90;
l2=l2tt2.angle';
l2(l2<6)=0;
l2(l2>90)=90;
```

Appendix C

GAI

1) I used a Generative AI tool (e.g. ChatGPT or similar) in my report --> YES

2) I used a GAI tool as language editor (i.e. to correct grammar mistakes, etc.) --> NO

3) I used GAI to retrieve information --> YES

To figure out how to use MATLAB, see below.

5) I used GAI to get help in writing code --> YES

I used Ecosia AI chat to find the right functions in MATLAB, followed by looking them up on the MathWorks help center, generate code examples to understand the syntax but not copying code, and troubleshooting by asking about error messages. Basically as an alternative/supplement to google search and forums.

6) I used GAI for translations --> NO

7) I used GAI to generate graphs/images --> NO

8) I used GAI to help structuring my content --> NO

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