Achieving thermal comfort in naturally ventilated offices in Sao Paulo, Brazil

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List of Symbols	
T_{op}	Indoor Operative Temperature
$T_{air,in}$	Indoor Air Temperature
T_{mrt}	Indoor Mean Radiant Temperature
T_{rm}	Outdoor Running Mean Temperature
$T_{air,out}$	Outdoor Air Temperature
v_{air}	Air Velocity
rH	Relative Humidity

Achieving Thermal Comfort in Naturally Ventilated Offices in São Paulo, Brazil

Abstract

To make accurate building performance predictions all factors that influence results need to be understood. Occupant behavior (OB) has been identified as the greatest source of uncertainty. This is especially true for the South-American region as no research was found in literature studying building comfort related OB there. In this paper, measurement and simulation results for thermal comfort and OB regarding window opening and fan use are presented. The measurements showed that for 86.27% and 75.00% of the occupied time, for the warm and cold period respectively, the thermal comfort fell within the >90% acceptability limits (comfort class A) according to the adaptive comfort model. Based on the measurement data, a simulation model in the EnergyPlus EMS language for window opening and fan use behavior was developed, showing average absolute errors for predicting fan use and window opening of 0.018 and 0.010 respectively. Using simulation, adaptive behavior was idealized for achieving thermal comfort. This way, the time spent outside comfort class A was reduced by 76% and 25% for the warm and cold period respectively. Lastly, improving insulation levels of the building envelope reduced discomfort by a further 44% and 53%, to maintain comfort class A 98.0% and 90.9% of the time for the warm and cold period respectively.

keywords: Occupant Behavior, Brazil, Building Performance Simulation, EnergyPlus, Window Opening, Fan Use, Free-Running.

1 Introduction

Buildings are created to provide comfort and shelter from outside conditions. Currently, the additional challenge for building engineers is to achieve this with the lowest amount of energy consumption as regulations are becoming ever more stringent [1]. For this reason, investigating to what extent free-running climate control systems can provide thermal comfort gives insight for both new developments and the renovation of existing building stock.

Better understanding of the parameters that influence building performance will help to design better performing buildings. Currently, measured operational performance often does not match designed performance. This performance gap was investigated for 121 LEED-NC version 2 buildings and it was found that for 55% percent of the investigated buildings the difference between the predicted and measured energy consumption was more than 25%, with the largest mismatch as great as +280% as shown in Figure 1 [2].

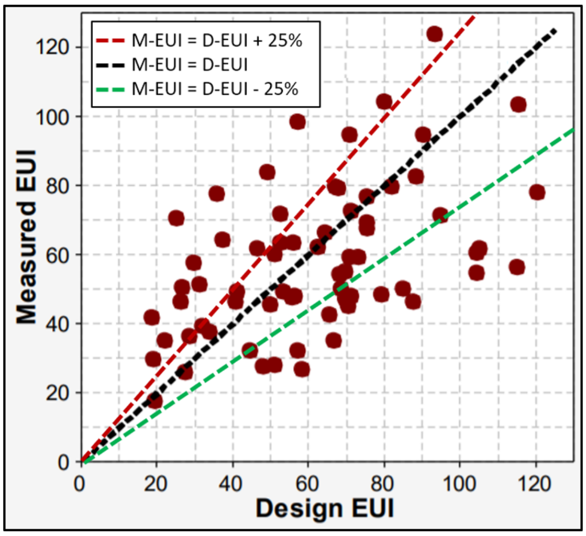


Figure 1: LEED Measured energy use intensity versus design energy use intensity for 121 LEED-NC certified buildings (adapted from [2])

This problem has incentivized the International Energy Agency to create the Energy in the Buildings and Communities Program. In Annex 53: Total Energy use in Buildings, the six main categories determining energy use in buildings have been determined as climate, building envelope, building energy and services systems, indoor design criteria, building operation and maintenance and occupant behavior (OB) [3]. Out of these categories the most significant knowledge gap exists regarding OB modeling as there lacks scientific and robust methods to define and model OB in buildings [4].

When measuring energy consumption for identical houses at a social housing project in the UK it was found that a difference of up to 54% in average energy consumption occurred, solely attributable to occupant influence [5]. Specification uncertainty in modeling, OB and poor operational practices were identified to be the leading causes of performance gaps [6], showing the need for more information on OB and quality standards in OB modeling.

Climate conditions and, to an extent, occupant preference and behavior are location dependent [7] and therefore it is important to gather spatially distributed data. Research efforts made at this point have mostly focused on certain markets, namely Europe, East-Asia and North America, leaving a knowledge gap in the Southern hemisphere. In a comprehensive comparative study on thermal comfort by Mishra & Ramgopal [8] only 4 out of 114 studied buildings were situated South of the equator. And a comparative study of 79 papers on OB by Gaetani et al. [9] did not include any South-American location. To help fill this gap, this research is focused on a situation in São Paulo, Brazil. An important market, with an estimated population of over 36 million in its greater metropolitan area [10], which is ∼17.2% of Brazil's population and ∼0,5% of the world's population.

Up until late in the previous century, buildings in Brazil were not often fitted with heating or cooling systems. The use of passive measures like thermal mass, shading and natural ventilation or low energy measures like fans was prevalent [11]. After the dictatorship ended in 1985, energy costs dropped and climate control technology became readily available which changed building design towards active, less energy efficient concepts [12]. To facilitate the global energy transition, it is important to learn from historically proven concepts and translate these into modern solutions [13].

Occupants of naturally ventilated buildings are comfortable in a wider temperature bandwidth than occupants of buildings with central heating, ventilation and air-conditioning (HVAC) systems without individual control [14]. Also, there is greater adaptation to prevailing outside climate conditions, suggesting an energy saving potential. Using measurement results obtained in North-America, Europe, Asia and Australia the ASHRAE 55 standard has been created [15]. This standard has since been validated for the sub-tropical climate zone of Brazil [16]. In open-plan or multi-occupant offices individual control is seldom available which makes natural ventilating a possibly promising strategy [17].

As can be seen in Figure 2, in the ASHRAE 55 standard naturally ventilated buildings allows for a higher thermal comfort bandwidth between 80% acceptability limits than mechanically ventilated buildings without individual control.

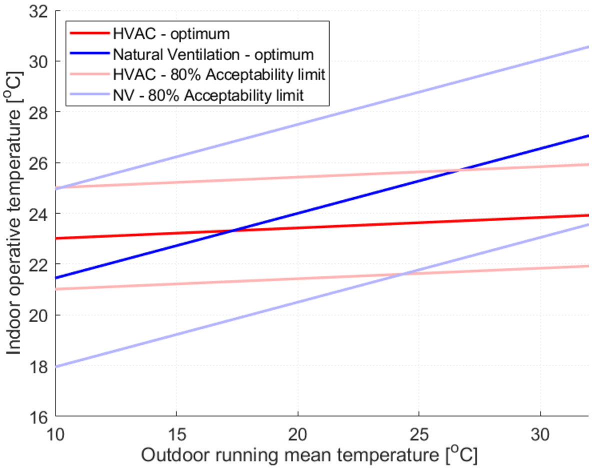


Figure 2: Adaptive thermal comfort for naturally ventilated buildings vs. thermal comfort for mechanically ventilated buildings without individual control [15]

The figure also shows that correlation between outdoor running mean temperature (T_{rm}) and preferred indoor operative temperature (T_{op}) is stronger, allowing for lower temperatures in cold periods and higher comfort temperatures in warm periods. With:

$$\text{HVAC-optimum} = 0.041 * T_{rm} + 22.6$$

$$\text{NV-optimum} = 0.31 * T_{rm} + 17.8$$

where:
$T_{rm} = 0.34T_{t-1} + 0.23T_{t-2} + 0.16T_{t-3} + 0.11T_{t-4} + 0.08T_{t-5} + 0.05T_{t-6} + 0.03T_{t-7}$

T_{t-n} = Daily mean outdoor air temperature n days before.

The increased flexibility and adaptation shown could make it possible for free-running buildings to provide comfort to its occupants. This paper studies to what extent this strategy can be successful in the sub-tropical climate of São Paulo. The aim is to improve thermal comfort for the occupants of the studied building. Also, the study will give insight into the ability to provide occupant comfort for free-running naturally ventilated buildings in a sub-tropical climate. In a bigger perspective, the energy savings potential of free-running systems can be of great importance in the current energy transition as we strive to create (nearly) zero energy buildings [18].

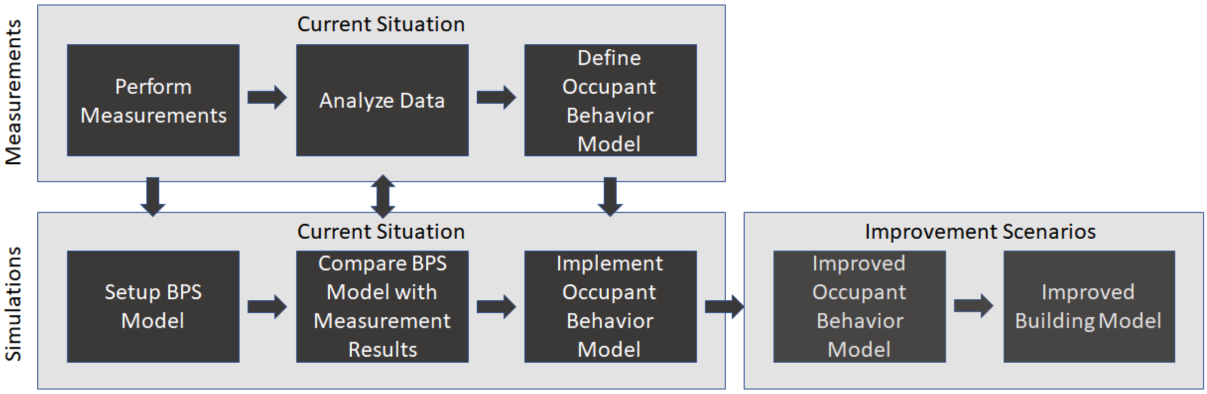


Figure 3: Methodology flowchart

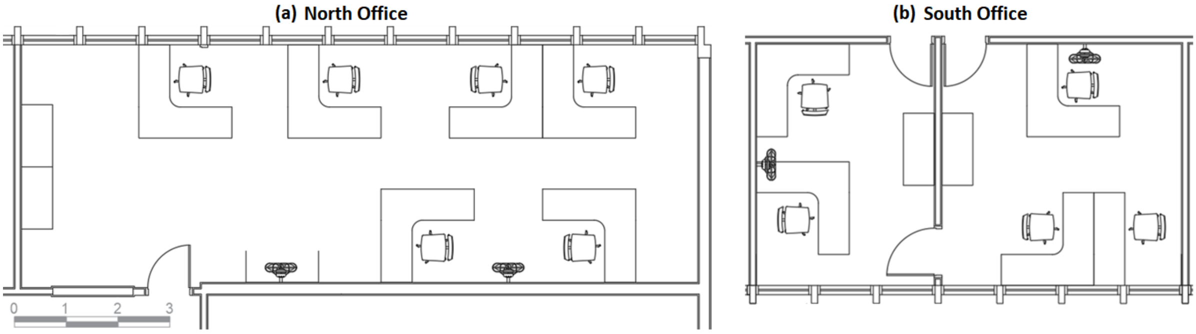
2 Method

To investigate the ability to provide thermal comfort for a free-running building in the sub-tropical climate of São Paulo, measurements of several environmental parameters and OB are performed in the naturally ventilated offices of the University Hospital at the University of São Paulo. Occupants can interact with operable windows, wall-mounted fans and swiveling horizontal blinds to achieve thermal comfort. The results are analyzed to find both comfort issues and relationships between environmental parameters and OB, these relationships are defined in linear models. A building performance simulation (BPS) model of the measured offices is created in EnergyPlus (E+) and the linear models are used to create and calibrate OB models representing the measured situation. After this has been achieved, the E+ model is used to study adapted OB aimed at achieving thermal comfort. Lastly, improved building insulation levels are modeled to study if building improvements can help to provide thermal comfort for the buildings users. An overview of the methodology is shown in Figure 3.

2.1 Measurements

Measurements on thermal conditions and room-state were taken during two different periods in two different offices. One six-employee office on the North side (Figure 4a) was studied during a warm period (late February to March) to assess overheating and two interconnected offices on the South side (Figure 4b), with two and three employees, were studied during a cold period (April to May) to assess exceeding of minimum comfort temperatures. The door connecting these offices was always open, creating a single thermal zone and this has been analyzed and simulated as such. Ideally, both offices would be studied both periods, but there was a limitation to the amount of time and measurement equipment available.

Data on outside climate conditions were obtained from a nearby measurement station located at the university campus. Inside thermal comfort measurements were taken with calibrated equipment (Testo & Delta-Ohm) during office hours and 24/7 with purpose-built arduino-based measurement equipment. This equipment also measured inside air quality, lighting and room-state regarding fan and window use. A time-lapse camera was used


(a) North Office

(b) South Office

Figure 4: Plan view of measured offices

to capture interactions with the blinds and to validate window position measurements. The parameters that were measured can be found in Table 1 and a complete overview of the measurement equipment in Appendix A. Thermal comfort measurements from the purpose-built equipment were calibrated using data from the Testo and Delta-Ohm equipment.

Spot measurements of the thermal conditions in thermal zones surrounding the measured offices were performed to assess whether interior partitions can be considered adiabatic. Using measurements and available CAD-drawings, the physical properties of the building, such as dimensions and material characteristics, were determined to define the BPS-model. Measurements of outdoor conditions are used to define the input conditions in the BPS-model.

Thermal comfort performance is evaluated by the percentage of time spent in comfort classes, with comfort class A where occupant satisfaction is >90%, comfort class B where satisfaction is between 80% and 90%, with Bw and Bc for too high and too low temperatures respectively and comfort class C where satisfaction is <80%, with Cw and Cc for too high and too low temperatures respectively. This is graphically illustrated in figure 5.

2.2 Data Analysis

The measurement results were analyzed to find correlation between environmental parameters and adaptive behavior. The expected relationship between a predicting parameter and a binary outcome is shown in Figure 6. A statistical analysis of relationships between environmental parameters (predictors) and adaptive behavior was performed to obtain the most significant predictors for adaptive behavior. These relationships were further studied using carpetplots to be able to visually compare environmental parameters and adaptive behaviors over time. After this, the relationships between predictors and adaptive behaviors are plotted and linear models for fan use and window opening behavior are obtained. These linear models are used to create a model of the measured behavior in E+ for a period with comparable climatic conditions, using EMS for implementing the stochastic model.

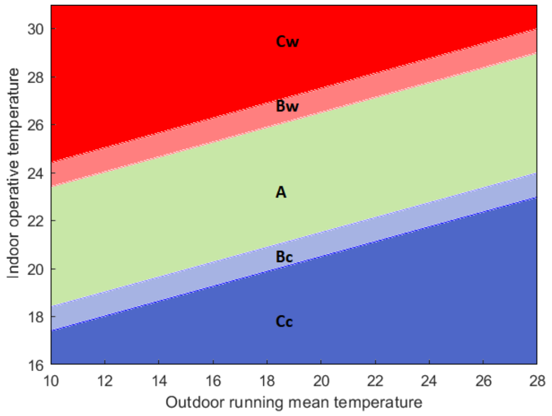


Figure 5: Thermal comfort classes using the adaptive thermal comfort standard, with comfort class A in green, comfort classes Bw and Cw in red and comfort classes Bc and Cc in blue

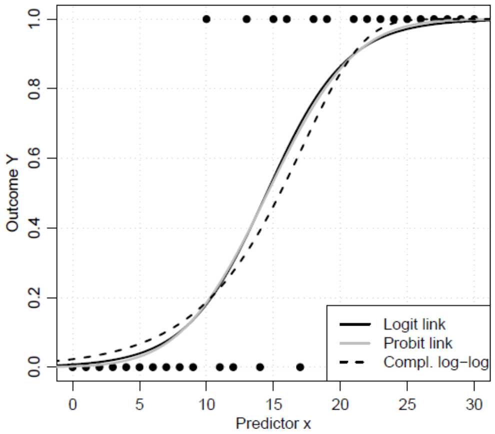


Figure 6: Comparison of the logit, probit and complementary log-log link functions for binary datasets [19]

	Category	Parameter
Inside	Thermal Comfort	T_A [^oC], T_R [^oC], v_{air} [ms^{-1}], rH [%]
	Air Quality	CO_2 [ppm], VOC [$CO_{2,ppmeq}$]
	Lighting Conditions	Work-plane illuminance [lux], facade luminance [lux]
	Occupant Behavior	Window [% open], Blinds [^{o} open], Fan [bin], Occupancy [bin]
Outside	Climate Conditions	T_A [^oC], rH [%], v_{air} [ms^{-1}]

Table 1: Measurement parameters

2.3 BPS Model of the Current Situation

BPS Model and Boundary Conditions
The BPS model input was defined using the previously obtained measurement data and CAD-drawings. Each room was modeled as one thermal zone, with the ceiling cavity above the lowered ceiling modeled as a separate thermal zone. The building facade is modeled with horizontal blinds and operable sliding windows. Fans were modeled as providing a certain amount of air velocity when activated. Results from outdoor weather measurements were used to find a comparable period in available International Weather for Energy Calculations (IWEC) climate data from the year 2002.

Occupant Behavior
A stochastic time-depedendent Markov chain model was developed based on the validated window opening model by Haldi & Robinson using the energy management system (EMS) functionality of E+ [20], which was created based on measurement data from Switzerland. The modeled values for environmental predictors that trigger adaptive behavior were adapted to reflect the measured behavior at the University Hospital offices in São Paulo. Survival modeling was introduced to reduce the chance of quick succession of opposite adaptive behaviors and to compensate for the overestimation of the overall amount of adaptive behaviors occurring in Markov chain models [21]. For fan use, there was no readily available comparable model found in literature. The measurement data was used to create and fit a stochastic Markov chain survival model for fan use in the EMS language of E+.

2.4 Investigating Operational Strategies and Building Improvements

Operational Strategies
Four operational strategies were compared here, an overview is provided in Table 2. The first strategy mimics the measured behavior (Measured). In the second strategy the windows are open and the fans are on during occupancy (On), when there is no occupancy the fans are off and windows are closed. In the third strategy the windows are closed and the fans are off (off). These last two strategies form two extremes at either end of the spectrum to create a baseline comparison. For the last strategy it was attempted to create the ideal situation for interacting with the building, regarding window opening and fan use, to improve thermal comfort as much as possible (Ideal). This was done by using information from the model to make an informed decision about whether to maintain the current window and fan state or to change it. The only stochastic element is a survival model that was implemented to reduce the chance of quick subsequent changes. Combining these strategies gives 16 scenarios to be simulated, but the focus will lie on the four scenarios with equal strategies for fan and window use.

Strategy	Fan Use	Window Opening
Measured	Measured Behavior	Measured Behavior
On	Always On	Always Open
Off	Always Off	Always Closed
Ideal	Idealized Behavior	Idealized Behavior

Table 2: Simulation strategies for OB

Building Improvements
Further simulations were performed where the benefit of adaptations to the building was assessed by adapting the model to include reduced infiltration, increased wall insulation and improved window quality as can be seen in Table 3. These scenarios were coupled to the idealized behavior scenario to achieve the best possible result regarding thermal comfort.

Scenario	Infiltration	Wall Insulation	Window Quality
Current	1 ACH	0 cm	single pane
Medium	0.5 ACH	8 cm	double pane
High	0 ACH	15 cm	triple pane

Table 3: Building improvements strategies

2.5 Reliability and Robustness

To achieve reliable results from a stochastic model regarding statistical mean and deviations a number of simulations need to be performed [22]. Mean values are found to be reliably attained after 10 simulation runs, but the standard deviation can require as much as 100 repetitions to achieve reliable results, depending on the internal variance of the model [23]. The actual number of iterations required is analysed in this study. The suggested time interval for accurate modeling of OB is to be a maximum of 15 minutes. If simulation time permits, a time interval of 5 minutes provides accurate results with very little benefit to further reduction beyond a 5-minute timestep [23].

The E+ EMS code for the OB models is included in Appendix E.

3 Measurement Results and Derived OB Models

Here, the most important results will be presented. Because of continuous window opening and building infiltration there were no observed problems with air quality during the measurement period, so CO_2-levels and VOC's are not further discussed. Also, blind adaptations are discounted because they occurred too sporadically for any patterns to emerge. The blinds were left in a position to avoid direct sunlight on the windows in the North office and left open to receive daylight in the South office.

3.1 Measured Environmental Conditions

First, as the purpose-built equipment measures on a relative scale, this scale was calibrated by making measurements in an isothermal environment at several temperature levels between 10^oC and 30^oC. Next to this initial calibration, the indoor air temperature ($T_{air,in}$) results between the purpose-built and calibrated measurement equipment were compared to assess the reliability of the purpose-built equipment and the ability to use its data. The differences in mean measured air $T_{air,in}$ were -0.28^oC and $+0.21^oC$ for the North and South office respectively and the mean absolute error was $\pm 0.37^oC$ and $\pm 0.43^oC$ respectively. Different placement can explain part of the difference as the purpose-built equipment was wall-mounted on an interior wall and the calibrated equipment was placed on a tripod. Re-calibrating by equalizing the mean measured $T_{air,in}$ improved the reliability, making the mean absolute error at the North office $\pm 0.24^oC$, the maximum error 1.2^oC and for >90% of the values the difference was $<0.5^oC$. The mean absolute error at the South office became $\pm 0.32^oC$, the maximum error became 1.5^oC and for >80% of the values the difference was $<0.5^oC$. Where available, results from the calibrated measurement equipment are used in the analysis.

Between the two measurement periods there was a difference of ~3°C in mean outdoor air temperature ($T_{air,out}$). Figure 7 shows a boxplot of the mean, 80% confidence interval and the extreme values for the $T_{air,out}$ and the $T_{air,in}$. Appendix B shows the complete measurement results for $T_{air,out}$ and $T_{air,in}$ for both measurement periods.

Measurement results showed that v_{air} increased by $\sim 1\ ms^{-1}$ when fans were turned on, this value is used to calculate the T_{op} for both measurement and simulation results.

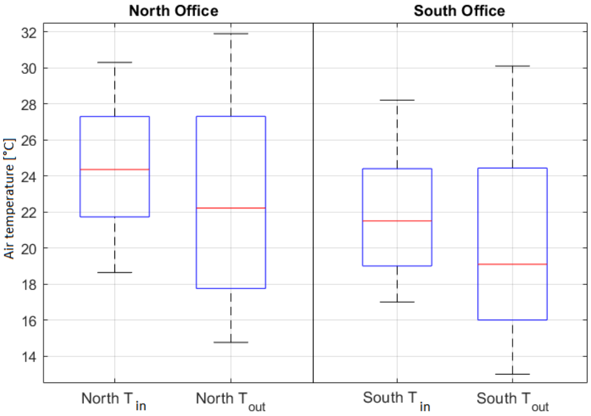


Figure 7: Measured indoor air temperature and outdoor air temperature

Results from spot measurements did not show significant temperature variations in the spaces surrounding the studied offices, therefore the offices have been modeled assuming interior partitions are adiabatic. The outside walls are concrete and brickwork without insulation and the windows have aluminum frames and single pane glass. From the available IWEC climate data from the year 2002, periods with comparable temperature statistics to the measured period where selected to perform the simulations. To compare the simulation input and measurement results, a boxplot of the mean, 80%-confidence interval and the extreme values of $T_{air,out}$ is shown in Figure 8.

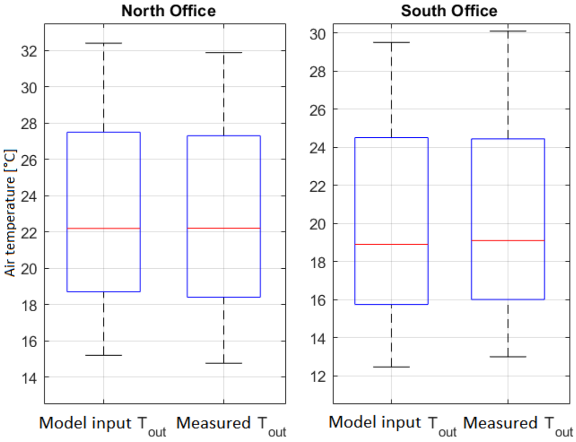


Figure 8: Comparison of measured outdoor air temperatures and outdoor air temperatures used as model input

When compared to the adaptive comfort criteria during occupied hours, it was measured that for the warm period 86.27%, 12.18% and 1.55% of the measurements fell in the A, B and C comfort classes respectively, with reduced comfort occurring mostly due to exceeding maximum comfort temperatures.

For the cold period 75.00%, 16.41% and 8.59% of the measurements fell in the A, B and C comfort classes respectively, with reduced comfort occurring due to exceeding minimum comfort temperatures. This is graphically represented in Figure 9.

3.2 OB: Statistical and Visual Data Analysis

Statistical Analysis

The statistically strongest predictor for fan use was found to be the $T_{air,in}$ with $R^2 = 0.59$ and $R^2 = 0.48$ for the warm and cold period respectively.

For window use the strongest statistical predictor was $T_{air,out}$. In the warm period an inverse correlation was observed with $R^2 = -0.47$, meaning windows were open at lower temperatures and closed at higher temperatures. During the cold period the correlation was found to be positive, with $R^2 = 0.38$. Therefore, two separate window use models are developed as these opposing results cannot be captured in one model.

Visual Analysis using Carpetplots

The statistical information informs about relationships, but does not give information on when exactly certain actions occur. Carpetplots were created and analyzed for all the relevant parameters. An example of such a carpetplot is given in Figure 10 (others are included in Appendix C). Here $T_{air,out}$ and the North office window state are depicted for the whole measurement period. It is immediately clear that windows are largely opened at the start of the workday and often closed early in the afternoon. Plotting the contours of the window state image over the $T_{air,out}$ image shows windows are opened when $T_{air,out}$ is low and closed when $T_{air,out}$ is high, giving confidence in the statistical analysis.

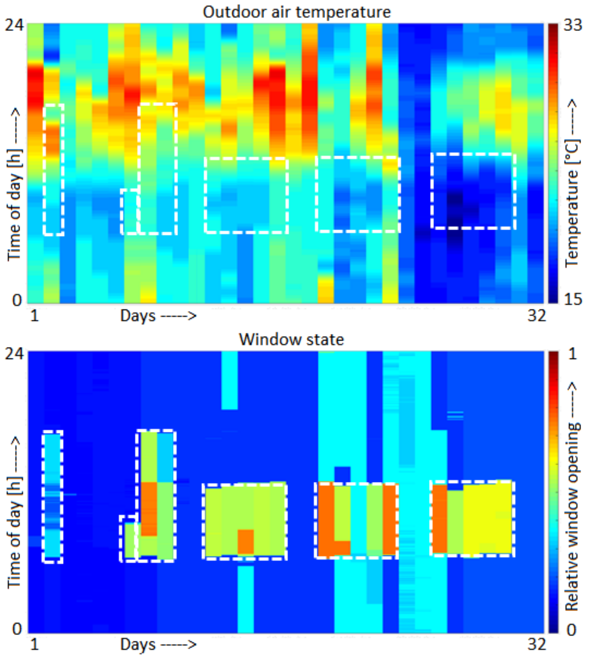


Figure 10: Carpet plot of measured outdoor air temperature and window state for the North office

3.3 OB Linear Model: Fan Use

The binary measurement results of the fan setting for both measurement periods were subdivided for the $T_{air,in}$ at their measurements time in 0.1 ^oC bins. For each bin the average fan setting was plotted against the $T_{air,in}$. Measurement results are shown by the blue circles in Figure 11. In the same figure, the red line represents the observed trend, showing increased fan use at higher $T_{air,in}$. Also

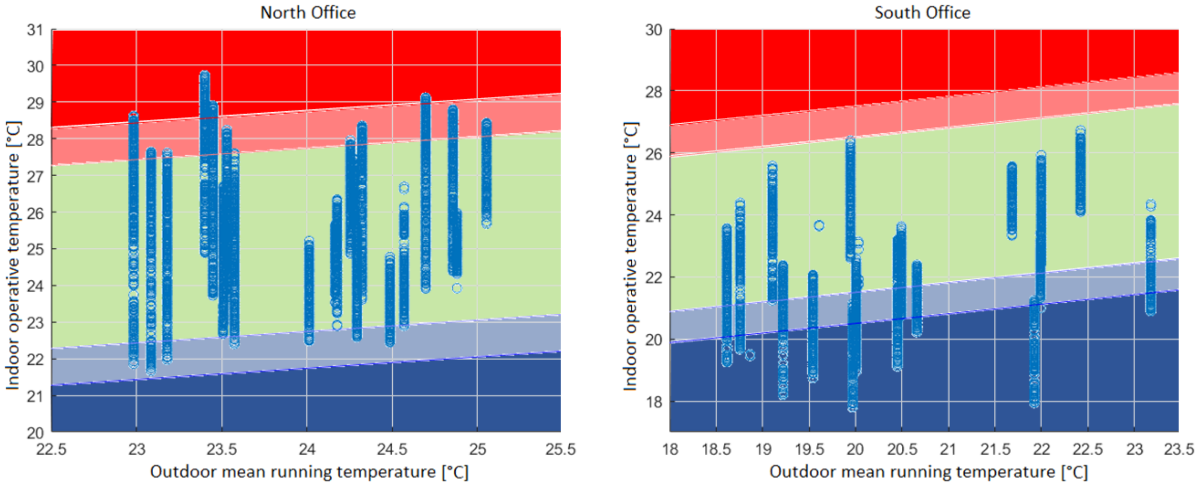


Figure 9: North and South office adaptive comfort results during occupancy

obvious is an underestimation of the trend curve for the lower temperatures and an overestimation for the middle temperature band. This leads to a mean absolute prediction error of 0.092 with a maximum error of 0.326.

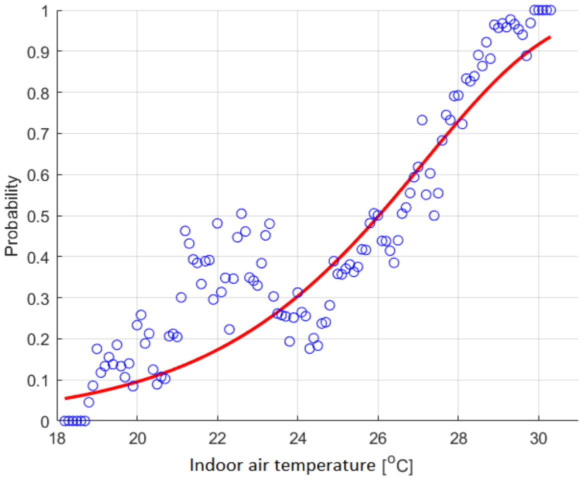


Figure 11: Measured fan use versus indoor air temperature

This suggests there might be another parameter influencing when the fan is used. Plotting the prediction curves grouped for 1^oC bins of the T_{rm} showed that fan use occurs at higher $T_{air,in}$ values for higher T_{rm} values due to adaptation. This is illustrated in Figure 12 by plotting the $T_{air,in}$ values where the trendline of the measured fan use reached 0.5 fan use probability for the different T_{rm} bins, showing a proportionate relationship between fan use and T_{rm}.

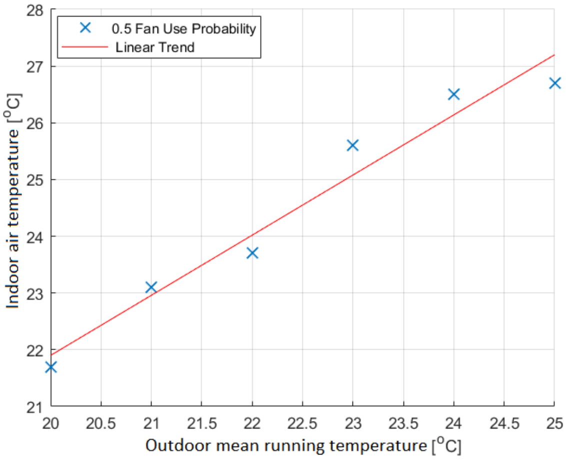


Figure 12: Measured fan use versus indoor air temperature subdivided in 1^oC bins of outdoor mean running temperature

For modeling purposes, the measured $T_{air,in}$ was offset relative to the mean T_{rm} using the following formulae:

$$T_{air,in} = T_{air,in} + (T_{rm} - T_{MRT,mean})$$

$$T_{MRT,mean} = 23.365[^oC]$$

With this adaptation, the improved result presented in Figure 13 was obtained. It shows a mean absolute prediction error of 0.054 with a maximum error of 0.170. This prediction curve for fan use is used for fitting the simulation model.

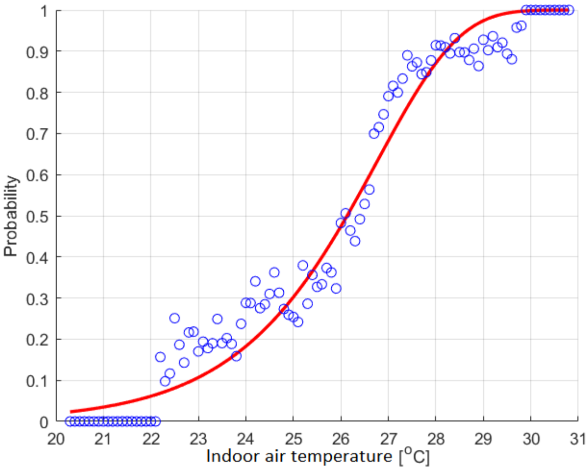


Figure 13: Fan use prediction curve, offset for outdoor mean running temperature

3.4 OB Linear Model: Window Opening

For both offices separately, the measurement results for window opening were subdivided for the $T_{air,out}$ at their measurements time in 0.1 ^oC bins. For each bin the average window state was plotted against the $T_{air,out}$. The results for both offices are shown in Figure 14. A mean absolute prediction error of 0.068 with a maximum error of 0.273 was found for the North office. The mean absolute prediction error for the South office was 0.032 with a maximum error of 0.128.

It was investigated if the inclusion of other parameters would improve the prediction accuracy. As for fan use, this was done by plotting subsets of the data subdivided according to other environmental parameters. This process yielded no significant prediction improvement for including $T_{air,in}$, T_{rm} or ΔT between $T_{air,in}$ and $T_{air,out}$, so only $T_{air,out}$ is used to predict window opening behavior.

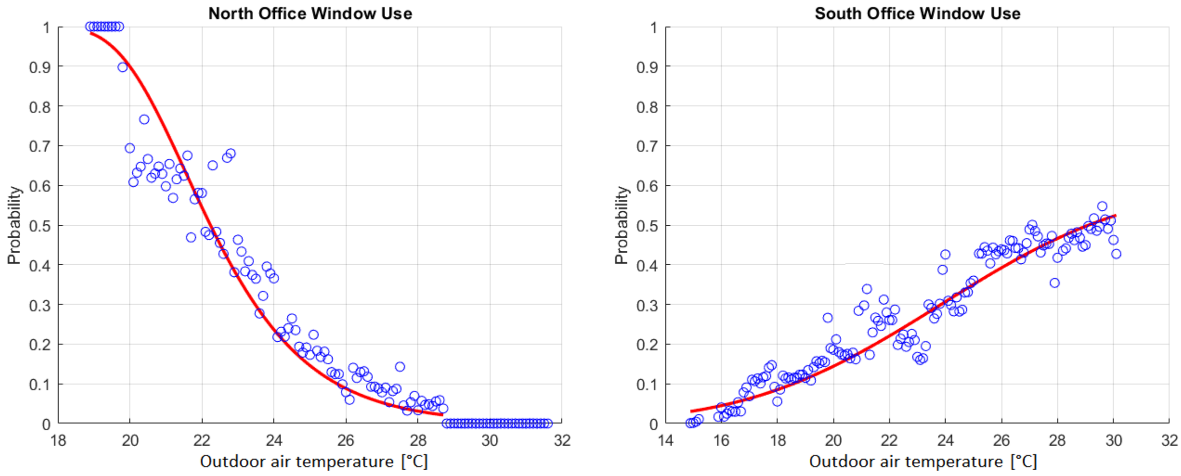


Figure 14: Window use prediction curve for North and South offices

4 Implementing Derived OB Models in E+

4.1 Fan Use Model

The fan use model is a Markov chain where the action (turning the fan on or off) is dependent of the current state of the fan and whether an action has recently been undertaken. If the fan is off, the chance of it being turned on increases exponentially with temperature. If the fan is on, the chance of it being turned off reduces exponentially with temperature. The probability is offset proportionately with T_{rm} so fan use occurs less when the T_{rm} is higher to simulate the measured adaptation. A comparison between the measured and simulated fan use behavior is shown in Figure 15. The average absolute error between the measured and simulated trend for fan use is 0.018 and the maximum error is 0.036.

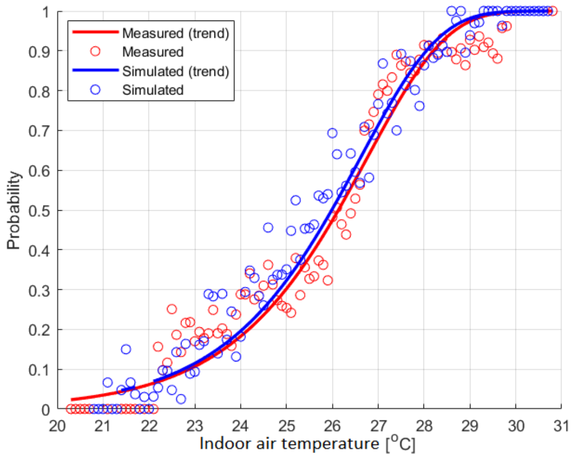


Figure 15: Comparison of measured and simulated fan use behavior

4.2 Window Use Models

Both window use models are based on the existing model by Haldi & Robinson [20], but this model had to be inverted for the North offices because window opening is inversely proportionate to the $T_{air,out}$. Also, a survival model was introduced to reduce the overall amount of adaptive behaviors, especially shortly after an adaptation has occurred. In reality the windows can be opened any percentage, but it was modeled as fully open or closed, as measurements showed windows were always opened at least 70% on use. Figure 16 shows the obtained simulation results compared to the measurements. The average absolute error between the measured and simulated trend for the North office is 0.008 and the maximum error is 0.015.

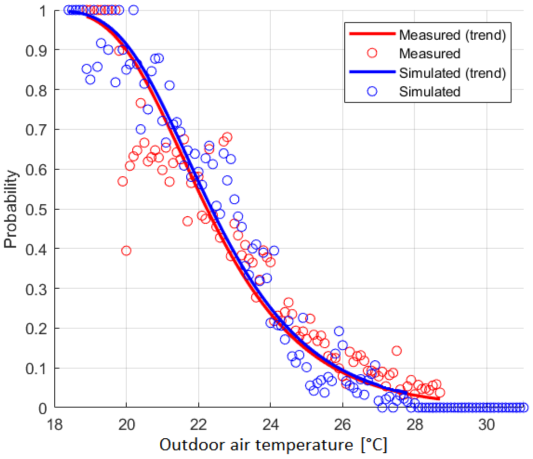


Figure 16: Comparison of measured and simulated window use behavior for the North office

In the South office, windows were never fully opened during the measurement period, this has been modeled by switching the window state between closed and 60% opened. The simulation results compared to the measurement results are shown in Figure 17. The average absolute error between the measured and simulated trend for the South office is 0.012 and the maximum error is 0.037.

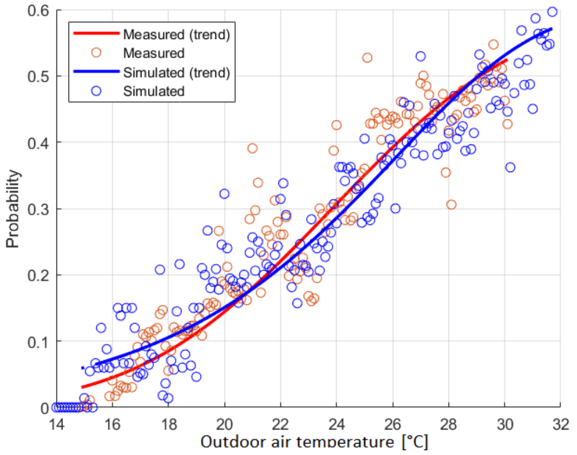


Figure 17: Comparison of measured and simulated window use behavior for the South office

Figure 18 shows a comparison of measured and simulated window use during a typical workweek. The outdoor weather conditions are not equal between the measured and simulated scenario, but it can be seen that occupant behavior shows good correlation without overestimating the number of adaptive behaviors.

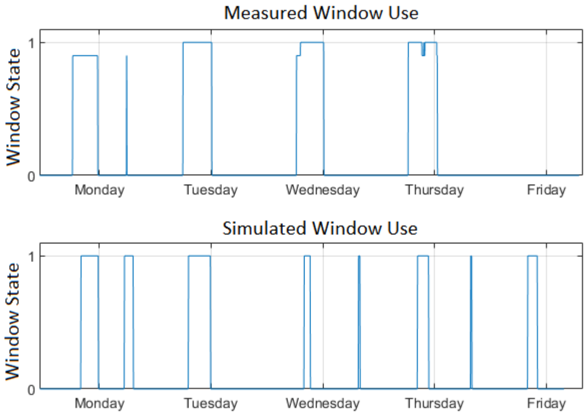


Figure 18: Comparison of measured and simulated window use behavior for a typical workweek

4.3 Stochastic Model Statistical Analysis

To assess the variance between simulation runs and the reliability of the results, the simulation has been run a number of times. With each extra run the mean value of the results, as well as the statistical information on variance and extremes, becomes more reliable. Figure 19 shows the mean, 50%-confidence interval and extreme values found for hours exceeding comfort class A for a different number of simulation iterations. The mean seems to reach a reliable value after 25 simulation runs. Increasing the number of iterations from 25 to 50 runs shows the confidence interval and extremes still change, but not to a major extent. Therefore 25 simulation iterations would be considered the best balance between reliability and simulation time. In the remainder of this paper the results from all 50 iterations are used, as they are already available.

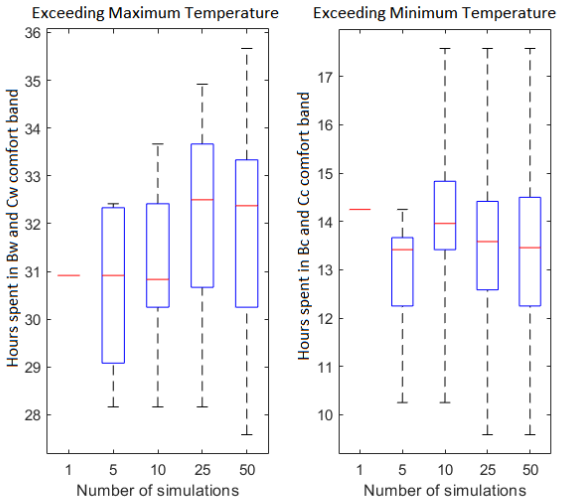


Figure 19: Statistical analysis of the number of simulation iterations required

5 Investigating Improvement Strategies

5.1 Investigating OB Strategies

The 'always on' and 'always off' models, as described in the methodology, form two extreme scenarios at either end of the spectrum. Using results from the measured and extreme scenarios, promising strategies were studied further, resulting in the idealized OB models. In the idealized fan use model the fans turn on when the current T_{op} is more than 0.5°C above the optimal comfort T_{op}. For window use, when the current T_{op} is below the optimal comfort T_{op}, windows are opened when the $T_{air,out}$ is higher than the current T_{op}. When the current T_{op} is above the optimal comfort T_{op}, windows are opened when the $T_{air,out}$ is below the current T_{op}. During warm periods nighttime ventilation is used for further cooling. For the idealized behavior scenario, this results in the relationships between temperature and room state during occupancy as shown in Figure 20.

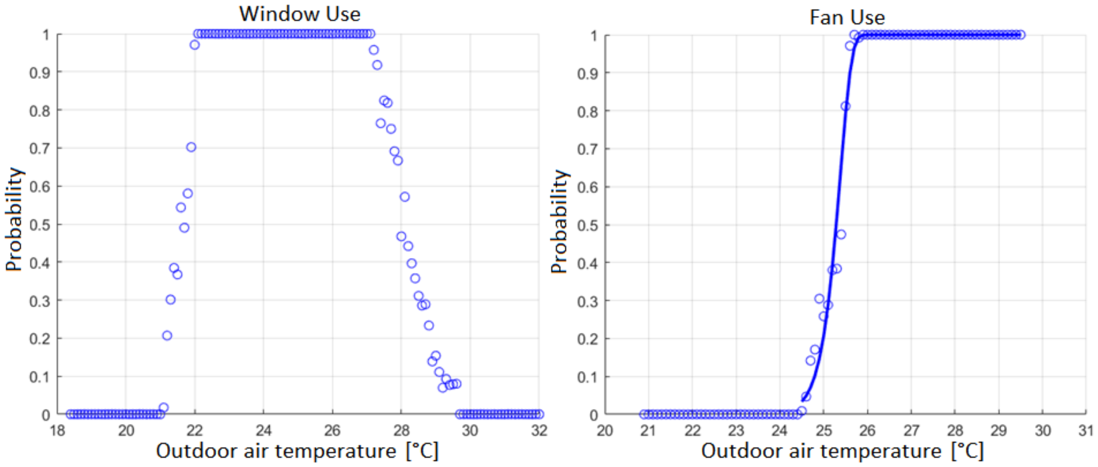


Figure 20: Results plot of the idealized simulation model for window use and fan use

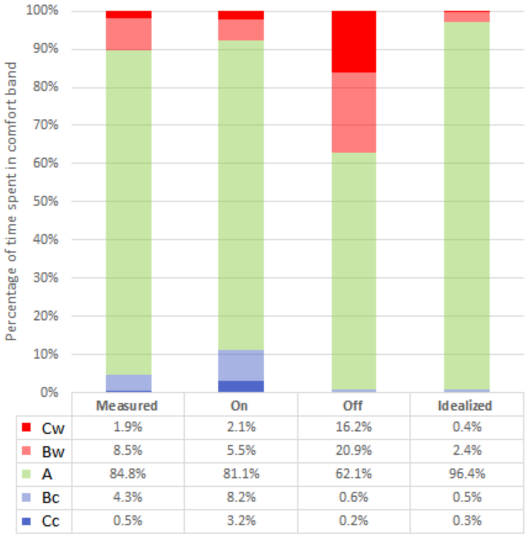
In the following section indoor comfort for the offices using the different simulation scenarios is reviewed. A full overview of all 16 scenarios can be found in appendix D, but here the focus lies on the 4 scenarios where fan use and window use both follow the same strategy, as the most extreme values and the measured scenario are included in this subset.

Warm Period - North Office

In Figure 21 the resulting adaptive comfort for the 4 scenarios is shown. The largest problem was found to be exceeding of maximum comfort temperatures. The percentage of time spent in comfort class A for the measured, always on, always off and idealized scenarios were 84.8%, 81.1%, 62.1% and 96.4% respectively. The 'always on' scenario gave similar results to the measured scenario, but suffered more from exceeding minimum temperatures with 8.2% versus 4.3%, where the measured scenario exceeded the maximum temperature more often with 8.5% versus 5.5%. The idealized scenario managed to reduce the time spent outside comfort class A by 76% from 15.2% to 3.6% and the time spent in comfort class C was reduced by 71% from 2.4% to 0.7% of the time. Hereby it is shown that better informed building interactions can greatly reduce exceeding of indoor comfort temperatures.

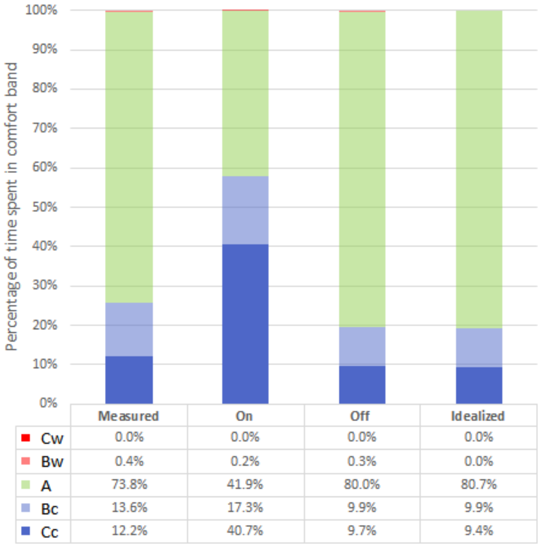
Cold period - South Office

Figure 22 shows the adaptive comfort results for the simulations of the South office during a cold period. There is hardly any overheating occurring, but exceeding minimum comfort temperatures is a



	Measured	On	Off	Idealized
🟥 Cw	1.9%	2.1%	16.2%	0.4%
🟥 Bw	8.5%	5.5%	20.9%	2.4%
🟩 A	84.8%	81.1%	62.1%	96.4%
🟦 Bc	4.3%	8.2%	0.6%	0.5%
🟦 Cc	0.5%	3.2%	0.2%	0.3%

Figure 21: North office simulated comfort class results for 4 different occupant behavior scenarios



	Measured	On	Off	Idealized
🟥 Cw	0.0%	0.0%	0.0%	0.0%
🟥 Bw	0.4%	0.2%	0.3%	0.0%
🟩 A	73.8%	41.9%	80.0%	80.7%
🟦 Bc	13.6%	17.3%	9.9%	9.9%
🟦 Cc	12.2%	40.7%	9.7%	9.4%

Figure 22: South office simulated comfort class results for 4 different occupant behavior scenarios

big issue. The percentage of time spent in comfort class C for the measured, always on, always off and idealized scenarios were 73.8%, 41.9%, 80.0% and 80.7% respectively. There is only a small difference between the always off and idealized scenarios, so window closing to avoid energy loss during cold periods is an important strategy to maintain thermal comfort. Compared to the measured scenario, the percentage of time spent outside comfort class A was reduced 25% in the idealized scenario, from 25.8% to 19.3% and 9.4% of the time was still spent in comfort class C. This simulation makes it clear that further measures would be necessary to maintain thermal comfort in cold periods.

5.2 Investigating Building Improvement Strategies

The previous section showed that thermal comfort can potentially be further improved. With simulation, building improvement scenarios are investigated to see if they can help to improve thermal comfort. The idealized scenario for OB is used in these simulations to achieve the best possible result.

Warm Period - North Office

In the warm period, idealizing OB for the current building state already achieved great improvements concerning indoor thermal comfort. The addition of extra insulation further improves this as can be seen in Figure 23. The time spent in comfort class A is increased from 96.4% to 97.5% and 98.0% for the current state, medium insulation and high insulation levels respectively. And time in comfort class C is avoided completely for the high insulation level.

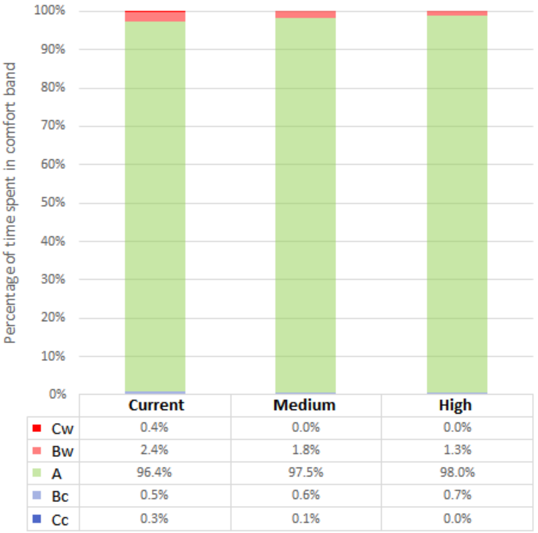


Figure 23: North office simulated comfort class results for current and improvement scenarios

Cold period - South Office

In the cold period discomfort was still observed for the idealized scenario and current building state during a large percentage of time. Building improvements increase the time spent in comfort class A from 80.7% to 85.1% and 90.9% for the current state, medium insulation and high insulation levels respectively as seen in Figure 24. Time spent in comfort class C is reduced by 49% and 70% by the medium and high insulation levels to 4.8% and 2.8% respectively.

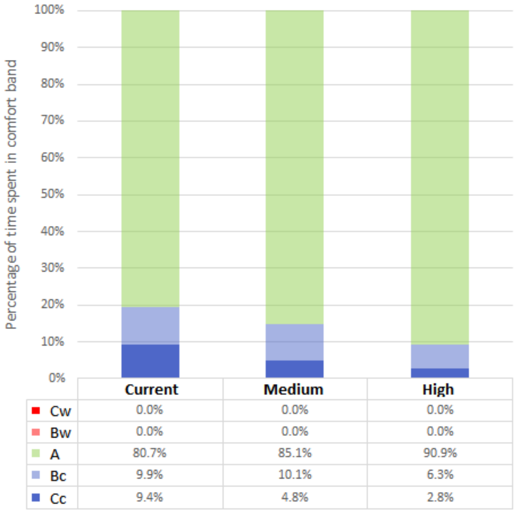


Figure 24: South office simulated comfort class results for current and improvement scenarios

6 Discussion

During the measurements it became clear that there were more thermal comfort issues due to exceeding minimum temperatures in cold periods on the shaded side of the building, than by exceeding maximum temperatures in warm periods on the sunny side of the building. The effective solar shading solution implemented in the building helped to reduce solar gains and overheating on the sunny side.

A significant reduction in discomfort was achieved by improving the interaction with the building systems. To achieve these results in real-life, the building user would need to be better informed about current inside and outside conditions (e.g. indoor and outdoor air temperatures) to be able to make informed decisions about using the fans and windows.

In this simulation exercise the offices were modeled separately, without interaction between the sunny and shaded sides of the building. It can be expected that interaction could have further positive effects on thermal comfort as, when desired, temperatures on the warmer, sunny side of the building can be reduced, while temperatures on the cooler, shaded side of the building can be increased by this interaction.

To further investigate the model's reliability, measurements and simulations using the same climatic conditions could be performed. Currently, a direct comparison is not possible as the weather data used in simulations is similar to the measured conditions, but not equal.

The measurement period did not include extreme temperature values as the lowest recorded outside temperature during all measurements was 13.0^{o}C and the highest was 31.9^{o}C. Though this is representative for typical daily minimum and maximum temperatures, Temperatures over 35^{o}C are common during summer and temperatures below 0^{o}C have been recorded as well [24]. Therefore, it is not recommended to design purely free-running buildings in this area, but to take note of passive design measures that can reduce the need for heating and cooling.

A full annual simulation of thermal comfort fell beyond the scope of this research, but would be interesting for a complete assessment of thermal comfort. The model presented here would be a good starting point for extending the research.

Building improvements have been limited to increasing insulation levels (walls and windows) and air tightness of the building facade, as this would be the most feasible improvement for the current building. The model could be adapted with other features, like increased thermal mass, double skin facade or phase-changing materials, to inform building designers about the possible benefits for newly designed buildings.

7 Conclusion

This research makes a contribution to the spatial distribution of knowledge on OB, as no other studies of window interaction or fan use in Brazil, nor in the whole region of South-America, have been found in literature.

The model simulating the measured results achieved a good representation of the real building and occupant behavior, making the simulation results a reliable source of information. As the weather data used in the simulations was similar, but not the exact measured weather data, the comparison between measurement results of OB and the simulation results, triggered by environmental predictors, gives a good indication. The model was able to make an accurate prediction of the room state for a certain temperature, with average absolute prediction errors of 0.018, 0.008 and 0.012 for fan use, North office window use and South office window use respectively.

To achieve reliable results for this stochastic model a minimum of 25 iterations is required and 50 runs would be recommended if time permits.

Solely by implementing a different strategy for interacting with building systems a significant reduction of discomfort was achieved. The percentage of time spent outside comfort class A was reduced by 76% from 15.2% to 3.6% of the time during the warm period and it was reduced by 25% from 25.8% to 19.3% during the cold period.

Thermal discomfort can be further reduced by implementing building improvements. Simulations show that by adding wall insulation, improving the window quality and reducing infiltration, spending time in comfort class C was avoided during the warm period and 98.0% of the time was spent within comfort class A. During the cold period 2.8% of the time was still spent in comfort class C with the high level of insulation, but this did constitute a 70% improvement relative to the current situation.

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Appendix

A - Overview of measurement equipment

Testo 435-4 - Multifunction meter

Built-in Pressure Sensor

	Absolute Pressure
Measuring range	+600 to +1150 hPa
Accuracy	±10 hPa

Thermal Velocity Probe

	Temperature - NTC	Humidity - Capacitive	Velocity - Hot wire anemometer
Measuring range	-20 to +70 ^oC	0 to +100 %rH	0 to +20 ms^{-1}
Accuracy	±0.3 ^oC	±2 %rH (+2 to +98 %rH)	±(0.03 ms^{-1} + 4 % of mv)

Globe Probe

	Temperature - Type K TC
Measuring range	0 to +120 ^oC
Accuracy	Class 1

Delta Ohm HD32.1 – Thermal Microclimate Data Logger

Globe Probe

	Temperature - Type K TC
Measuring range	-30 to 120 ^oC
Accuracy	Class 1 - ±0.2 ^oC

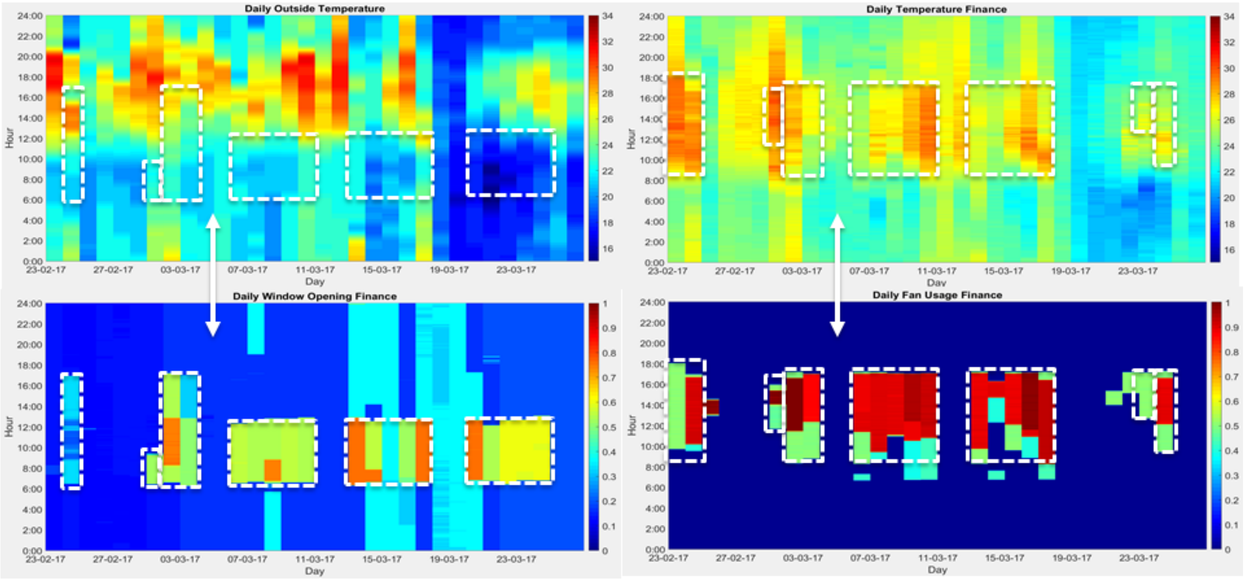
Relative humidity and temperature combined probe

	Temperature - NTC	Humidity - Capacitive
Measuring range	-30 to 120 ^oC	0 to +100 %rH
Accuracy	±0.3 ^oC	±1.5 %rH

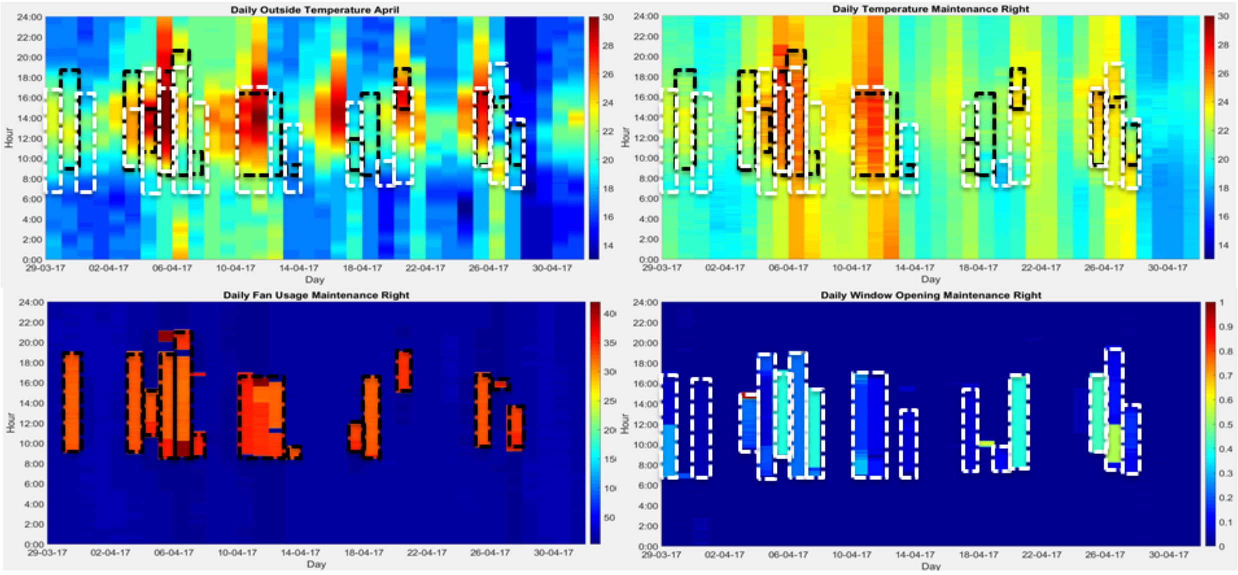
Omnidirectional hotwire probe

	Air speed
Measuring range	0.05 to 5 ms^{-1}
Accuracy	±(0.1ms^{-1} + 3% mv)

Appendix B - Carpetplots of adaptive behavior and temperatures

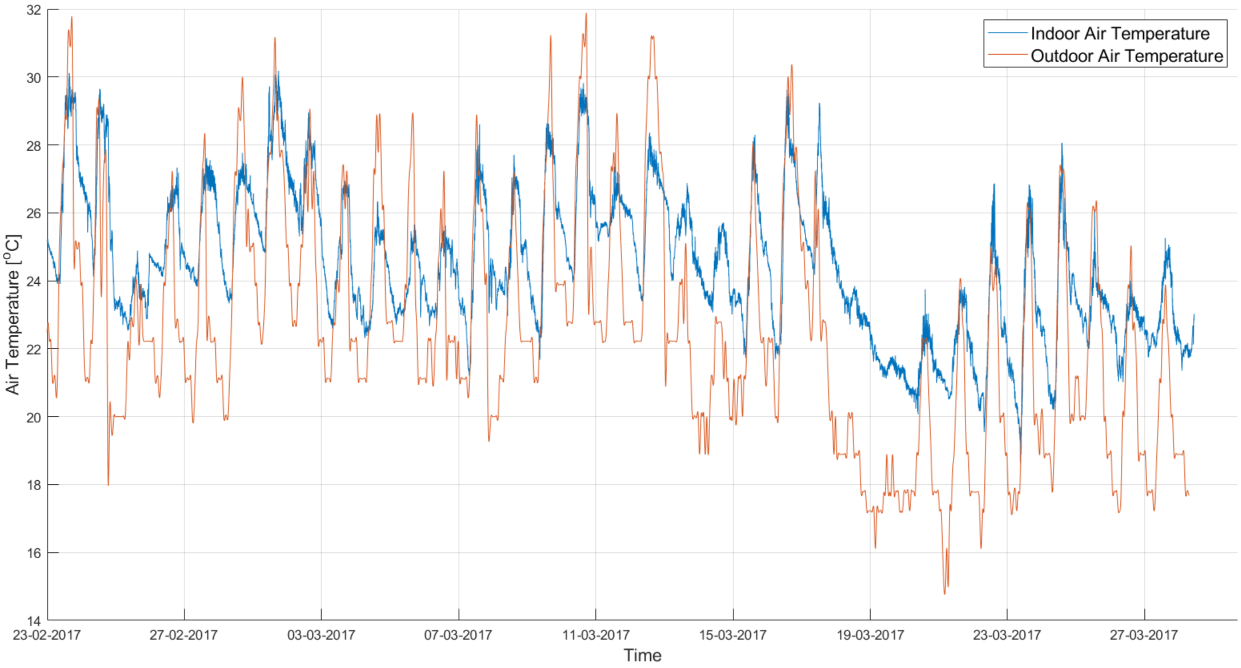


North Office carpetplots for indoor and outdoor air temperature, window state and fan state

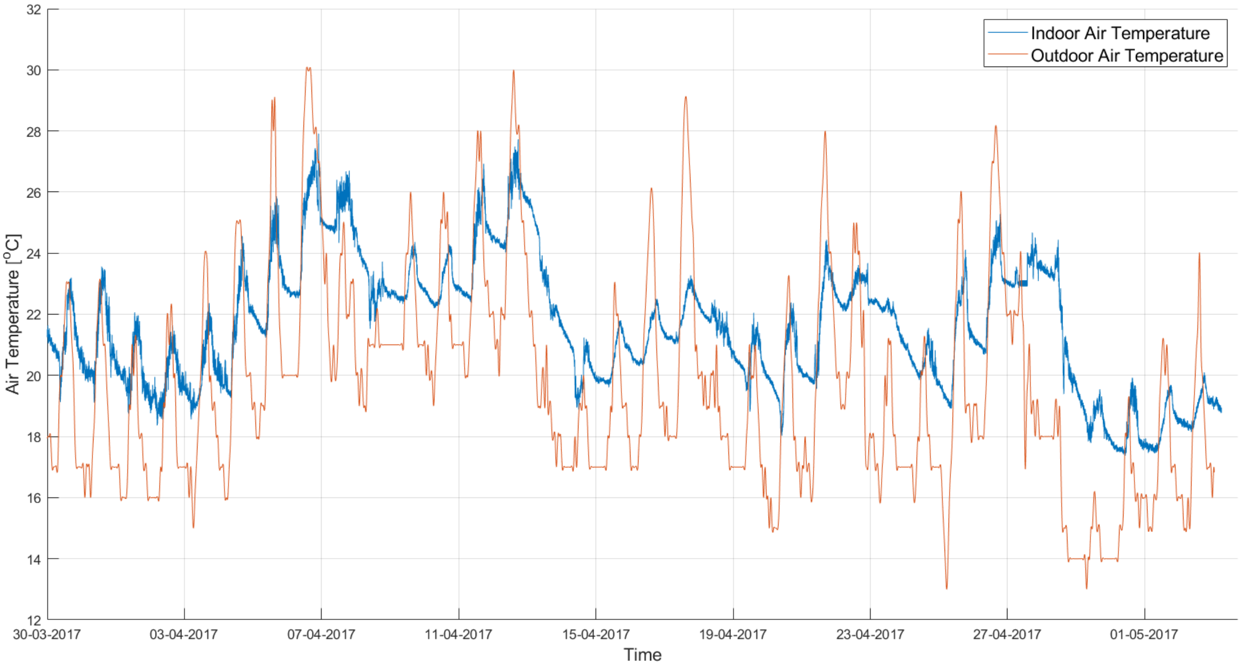


South Office carpetplots for indoor and outdoor air temperature, window state and fan state

Appendix C - Graphical representations of measured air temperatures

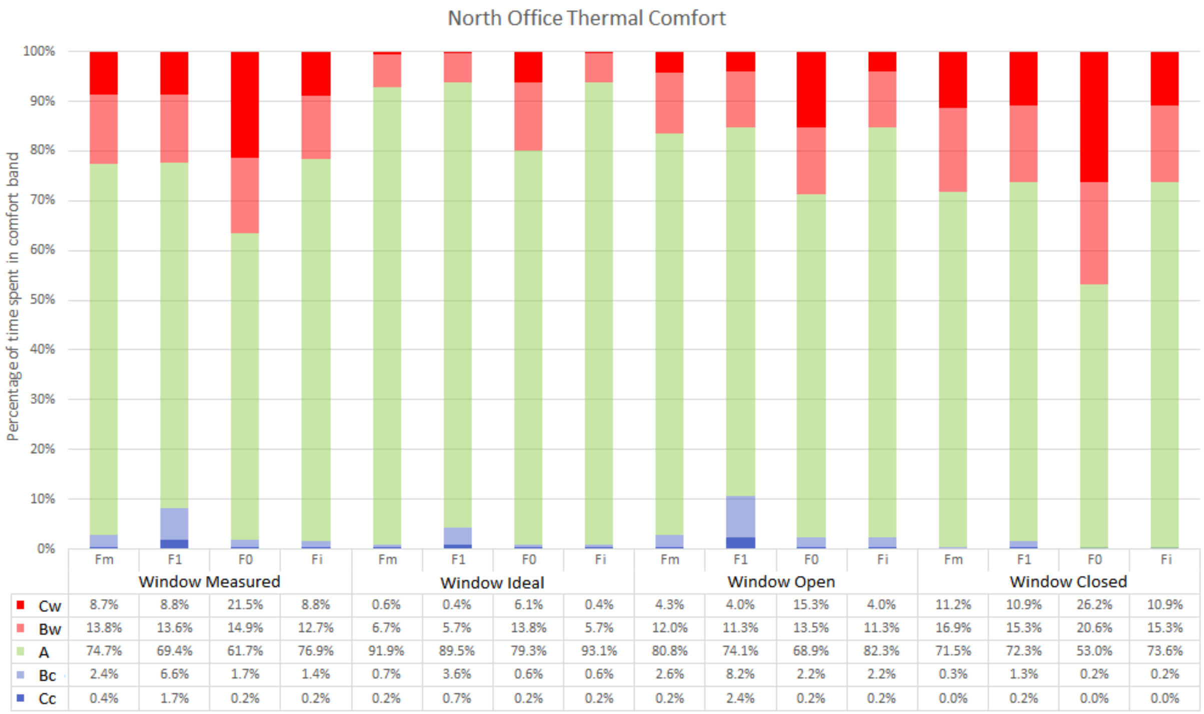


North Office measured indoor and outdoor air temperature



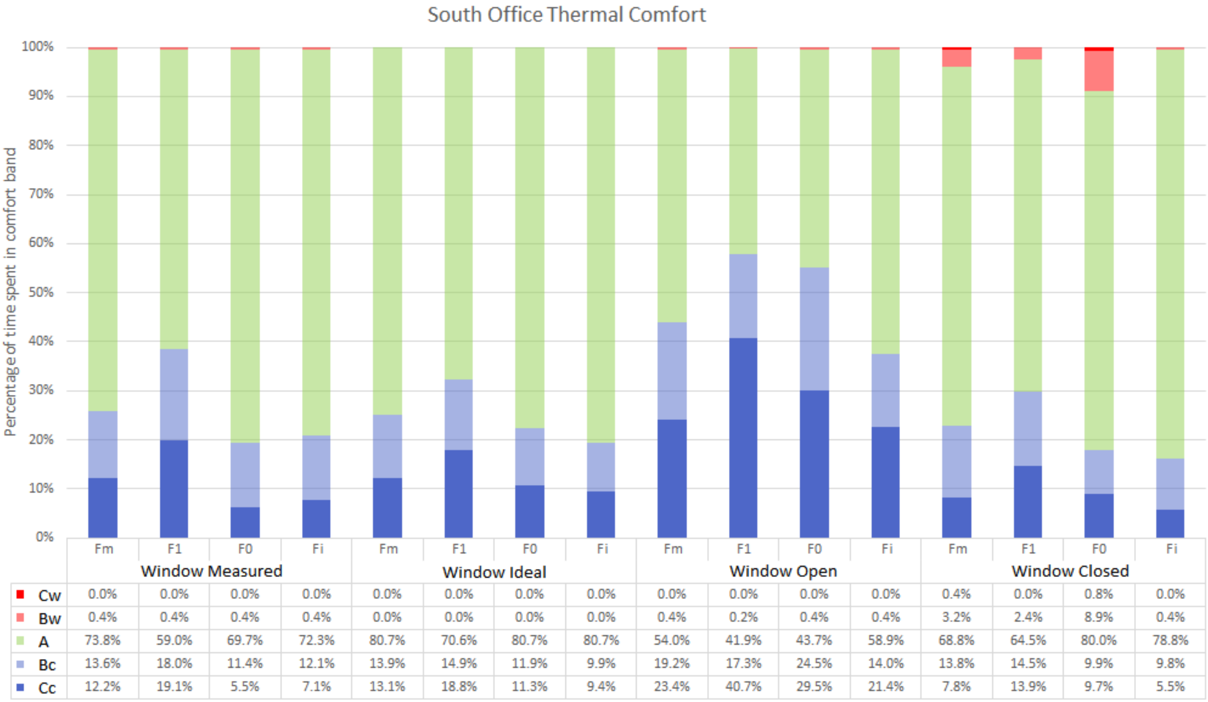
South Office measured indoor and outdoor air temperature

Appendix D - Full simulation results for behavioral permutations



	Window Measured				Window Ideal				Window Open				Window Closed			
	Fm	F1	F0	Fi	Fm	F1	F0	Fi	Fm	F1	F0	Fi	Fm	F1	F0	Fi
🟥 Cw	8.7%	8.8%	21.5%	8.8%	0.6%	0.4%	6.1%	0.4%	4.3%	4.0%	15.3%	4.0%	11.2%	10.9%	26.2%	10.9%
🟥 Bw	13.8%	13.6%	14.9%	12.7%	6.7%	5.7%	13.8%	5.7%	12.0%	11.3%	13.5%	11.3%	16.9%	15.3%	20.6%	15.3%
🟩 A	74.7%	69.4%	61.7%	76.9%	91.9%	89.5%	79.3%	93.1%	80.8%	74.1%	68.9%	82.3%	71.5%	72.3%	53.0%	73.6%
🟦 Bc	2.4%	6.6%	1.7%	1.4%	0.7%	3.6%	0.6%	0.6%	2.6%	8.2%	2.2%	2.2%	0.3%	1.3%	0.2%	0.2%
🟦 Cc	0.4%	1.7%	0.2%	0.2%	0.2%	0.7%	0.2%	0.2%	0.2%	2.4%	0.2%	0.2%	0.0%	0.2%	0.0%	0.0%

North office simulated comfort class results for all behavior scenarios with:
Fm: Fan Measured, F1: Fan On, F0: Fan Off, Fi: Fan Ideal



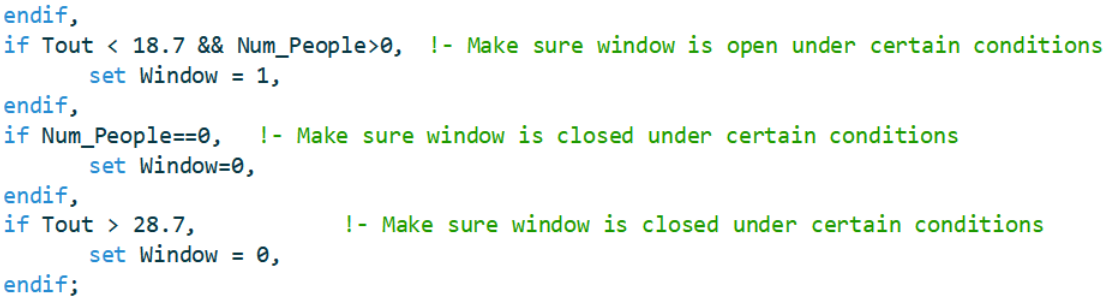
	Window Measured				Window Ideal				Window Open				Window Closed			
	Fm	F1	F0	Fi	Fm	F1	F0	Fi	Fm	F1	F0	Fi	Fm	F1	F0	Fi
🟥 Cw	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.8%	0.0%
🟥 Bw	0.4%	0.4%	0.4%	0.4%	0.0%	0.0%	0.0%	0.0%	0.4%	0.2%	0.4%	0.4%	3.2%	2.4%	8.9%	0.4%
🟩 A	73.8%	59.0%	69.7%	72.3%	80.7%	70.6%	80.7%	80.7%	54.0%	41.9%	43.7%	58.9%	68.8%	64.5%	80.0%	78.8%
🟦 Bc	13.6%	18.0%	11.4%	12.1%	13.9%	14.9%	11.9%	9.9%	19.2%	17.3%	24.5%	14.0%	13.8%	14.5%	9.9%	9.8%
🟦 Cc	12.2%	19.1%	5.5%	7.1%	13.1%	18.8%	11.3%	9.4%	23.4%	40.7%	29.5%	21.4%	7.8%	13.9%	9.7%	5.5%

South office simulated comfort class results for all behavior scenarios with:
Fm: Fan Measured, F1: Fan On, F0: Fan Off, Fi: Fan Ideal

Appendix E - EMS code

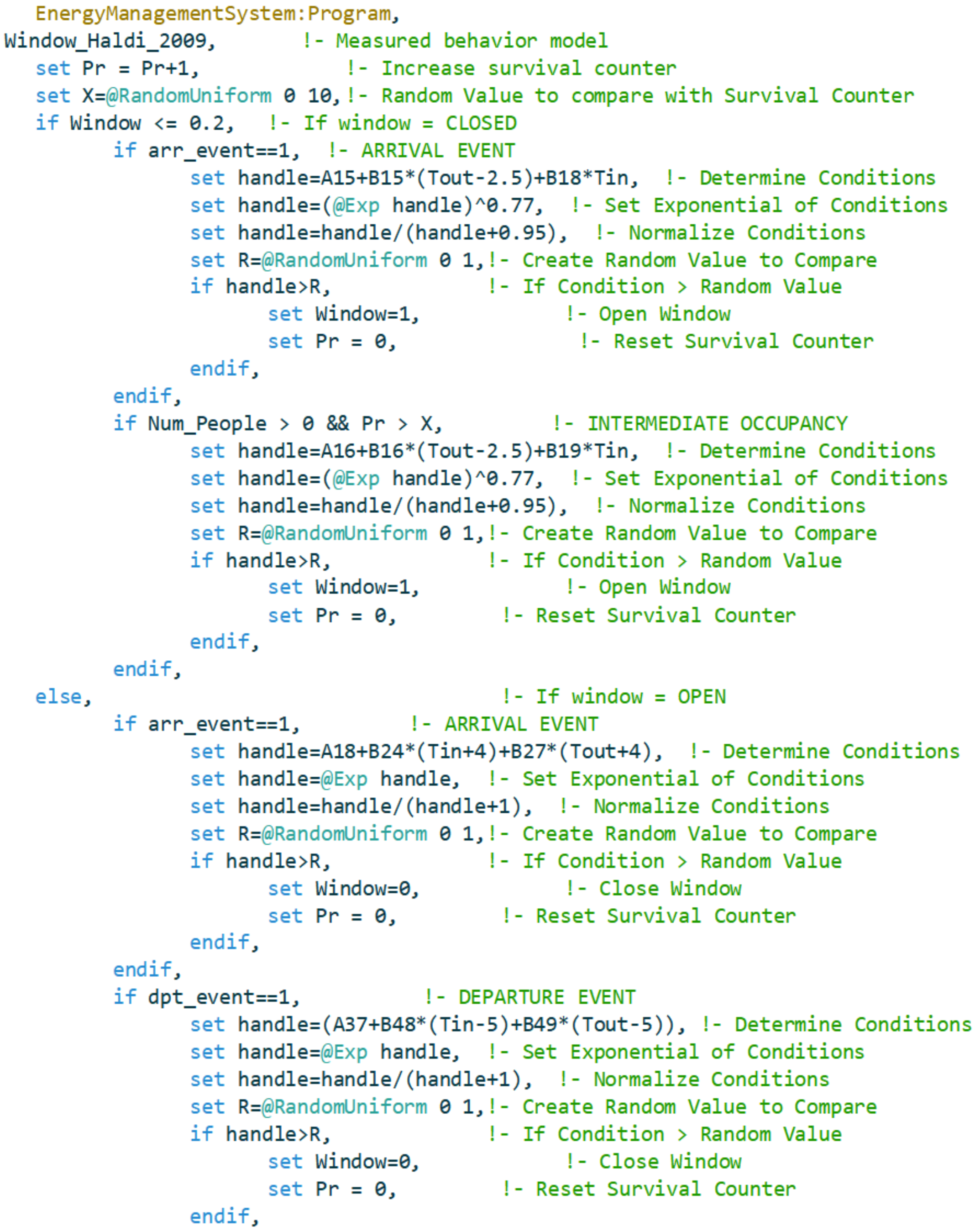
North Office - Warm Period - Window Opening as Measured

```
       EnergyManagementSystem:Program,
    Window_Haldi_2009,       !- Measured behavior model
       set Pr = Pr+1,            !- Increase survival counter
       set X=@RandomUniform 0 10,!- Random Value to compare with Survival Counter
       if Window <= 0.2,  !- If window = CLOSED
             if arr_event==1,  !- ARRIVAL EVENT
                    set handle=A15+B15*(2*(32-Tout))+B18*Tin,  !- Determine Conditions
                    set handle=@Exp handle,  !- Set Exponential of Conditions
                    set handle=handle/(handle+1),  !- Normalize Conditions
                    set R=@RandomUniform 0 1,!- Create Random Value to Compare
                    if handle>R,              !- If Condition > Random Value
                          set Window=1,             !- Open Window
                          set Pr = 0,                !- Reset Survival Counter
                    endif,
             endif,
             if Num_People > 0 && Pr > X,         !- INTERMEDIATE OCCUPANCY
                    set handle=A16+B16*(2*(32-Tout))+B19*Tin,  !- Determine Conditions
                    set handle=@Exp handle,  !- Set Exponential of Conditions
                    set handle=handle/(handle+1),  !- Normalize Conditions
                    set R=@RandomUniform 0 1,!- Create Random Value to Compare
                    if handle>R,              !- If Condition > Random Value
                          set Window=1,             !- Open Window
                          set Pr = 0,         !- Reset Survival Counter
                    endif,
             endif,
       else,                                  !- If window = OPEN
             if arr_event==1,         !- ARRIVAL EVENT
                    set handle=(A18+B24*(28-Tin)^1.8+B27*(28-Tout)^1.8),  !- Determine Conditions
                    set handle=@Exp handle,  !- Set Exponential of Conditions
                    set handle=handle/(handle+1),  !- Normalize Conditions
                    set R=@RandomUniform 0 1,!- Create Random Value to Compare
                    if handle>R,              !- If Condition > Random Value
                          set Window=0,             !- Close Window
                          set Pr = 0,         !- Reset Survival Counter
                    endif,
             endif,
             if dpt_event==1,           !- DEPARTURE EVENT
                    set handle=(A37+B48*((Tin-3)^0.8)+B49*((Tout-3)^0.8)),  !- Determine
Conditions
                    set handle=@Exp handle,  !- Set Exponential of Conditions
                    set handle=handle/(handle+1),  !- Normalize Conditions
                    set R=@RandomUniform 0 1,!- Create Random Value to Compare
                    if handle>R,              !- If Condition > Random Value
                          set Window=0,             !- Close Window
                          set Pr = 0,         !- Reset Survival Counter
                    endif,
             endif,
             if Num_People>0 && Pr > X,         !- INTERMEDIATE OCCUPANCY
                    set handle=(A19+B25*((Tin-2)^0.4)+B28*((Tout-2)^0.4)),  !- Determine
Conditions
                    set handle=@Exp handle,  !- Set Exponential of Conditions
                    set handle=handle/(handle+1),  !- Normalize Conditions
                    set R=@RandomUniform 0 1,!- Create Random Value to Compare
                    if handle>R,              !- If Condition > Random Value
                          set Window=0,             !- Close Window
                          set Pr = 0,         !- Reset Survival Counter
                    endif,
             endif,
```

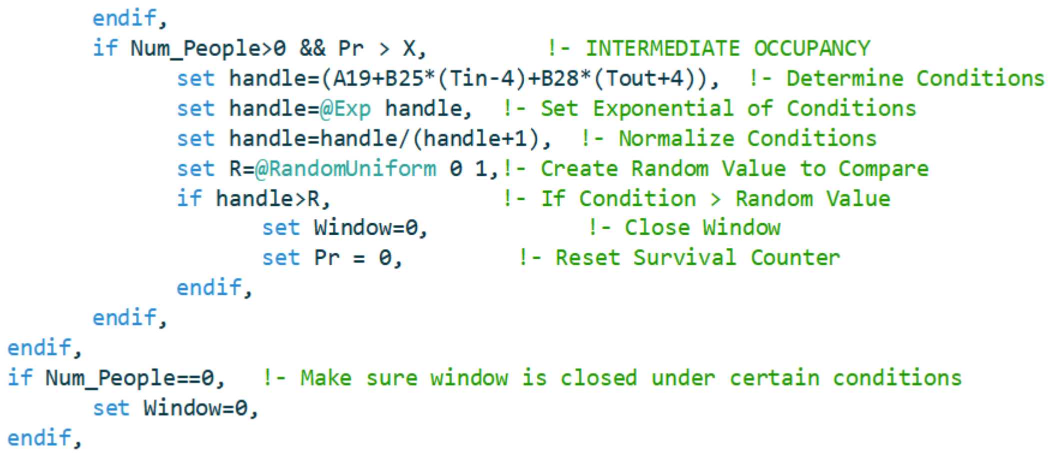


```
endif,
if Tout < 18.7 && Num_People>0,  !- Make sure window is open under certain conditions
      set Window = 1,
endif,
if Num_People==0,  !- Make sure window is closed under certain conditions
      set Window=0,
endif,
if Tout > 28.7,           !- Make sure window is closed under certain conditions
      set Window = 0,
endif;
```

South Office - cold period - Window Opening as Measured

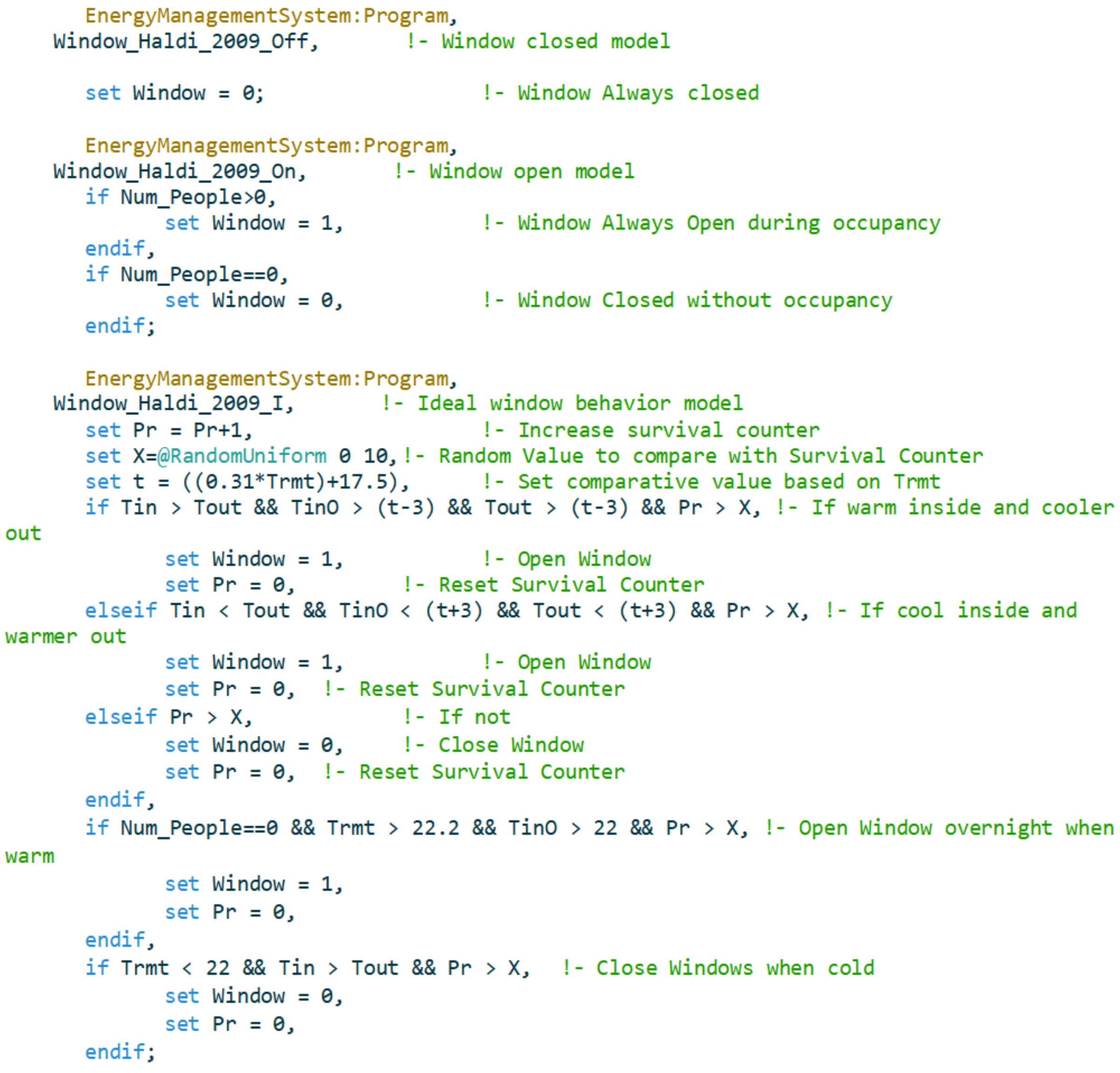


```
   EnergyManagementSystem:Program,
Window_Haldi_2009,       !- Measured behavior model
   set Pr = Pr+1,            !- Increase survival counter
   set X=@RandomUniform 0 10,!- Random Value to compare with Survival Counter
   if Window <= 0.2,   !- If window = CLOSED
         if arr_event==1,  !- ARRIVAL EVENT
                set handle=A15+B15*(Tout-2.5)+B18*Tin,  !- Determine Conditions
                set handle=(@Exp handle)^0.77,  !- Set Exponential of Conditions
                set handle=handle/(handle+0.95),  !- Normalize Conditions
                set R=@RandomUniform 0 1,!- Create Random Value to Compare
                if handle>R,            !- If Condition > Random Value
                      set Window=1,           !- Open Window
                      set Pr = 0,              !- Reset Survival Counter
                endif,
         endif,
         if Num_People > 0 && Pr > X,         !- INTERMEDIATE OCCUPANCY
                set handle=A16+B16*(Tout-2.5)+B19*Tin,  !- Determine Conditions
                set handle=(@Exp handle)^0.77,  !- Set Exponential of Conditions
                set handle=handle/(handle+0.95),  !- Normalize Conditions
                set R=@RandomUniform 0 1,!- Create Random Value to Compare
                if handle>R,            !- If Condition > Random Value
                      set Window=1,           !- Open Window
                      set Pr = 0,        !- Reset Survival Counter
                endif,
         endif,
   else,                                  !- If window = OPEN
         if arr_event==1,         !- ARRIVAL EVENT
                set handle=A18+B24*(Tin+4)+B27*(Tout+4),  !- Determine Conditions
                set handle=@Exp handle,  !- Set Exponential of Conditions
                set handle=handle/(handle+1),  !- Normalize Conditions
                set R=@RandomUniform 0 1,!- Create Random Value to Compare
                if handle>R,            !- If Condition > Random Value
                      set Window=0,           !- Close Window
                      set Pr = 0,        !- Reset Survival Counter
                endif,
         endif,
         if dpt_event==1,          !- DEPARTURE EVENT
                set handle=(A37+B48*(Tin-5)+B49*(Tout-5)), !- Determine Conditions
                set handle=@Exp handle,  !- Set Exponential of Conditions
                set handle=handle/(handle+1),  !- Normalize Conditions
                set R=@RandomUniform 0 1,!- Create Random Value to Compare
                if handle>R,            !- If Condition > Random Value
                      set Window=0,           !- Close Window
                      set Pr = 0,        !- Reset Survival Counter
                endif,
```



```
                endif,
                if Num_People>0 && Pr > X,          !- INTERMEDIATE OCCUPANCY
                      set handle=(A19+B25*(Tin-4)+B28*(Tout+4)),  !- Determine Conditions
                      set handle=@Exp handle,  !- Set Exponential of Conditions
                      set handle=handle/(handle+1),  !- Normalize Conditions
                      set R=@RandomUniform 0 1,!- Create Random Value to Compare
                      if handle>R,             !- If Condition > Random Value
                            set Window=0,            !- Close Window
                            set Pr = 0,         !- Reset Survival Counter
                      endif,
                endif,
          endif,
          if Num_People==0,   !- Make sure window is closed under certain conditions
                set Window=0,
          endif,
```

Both Offices - Other Window Opening Models



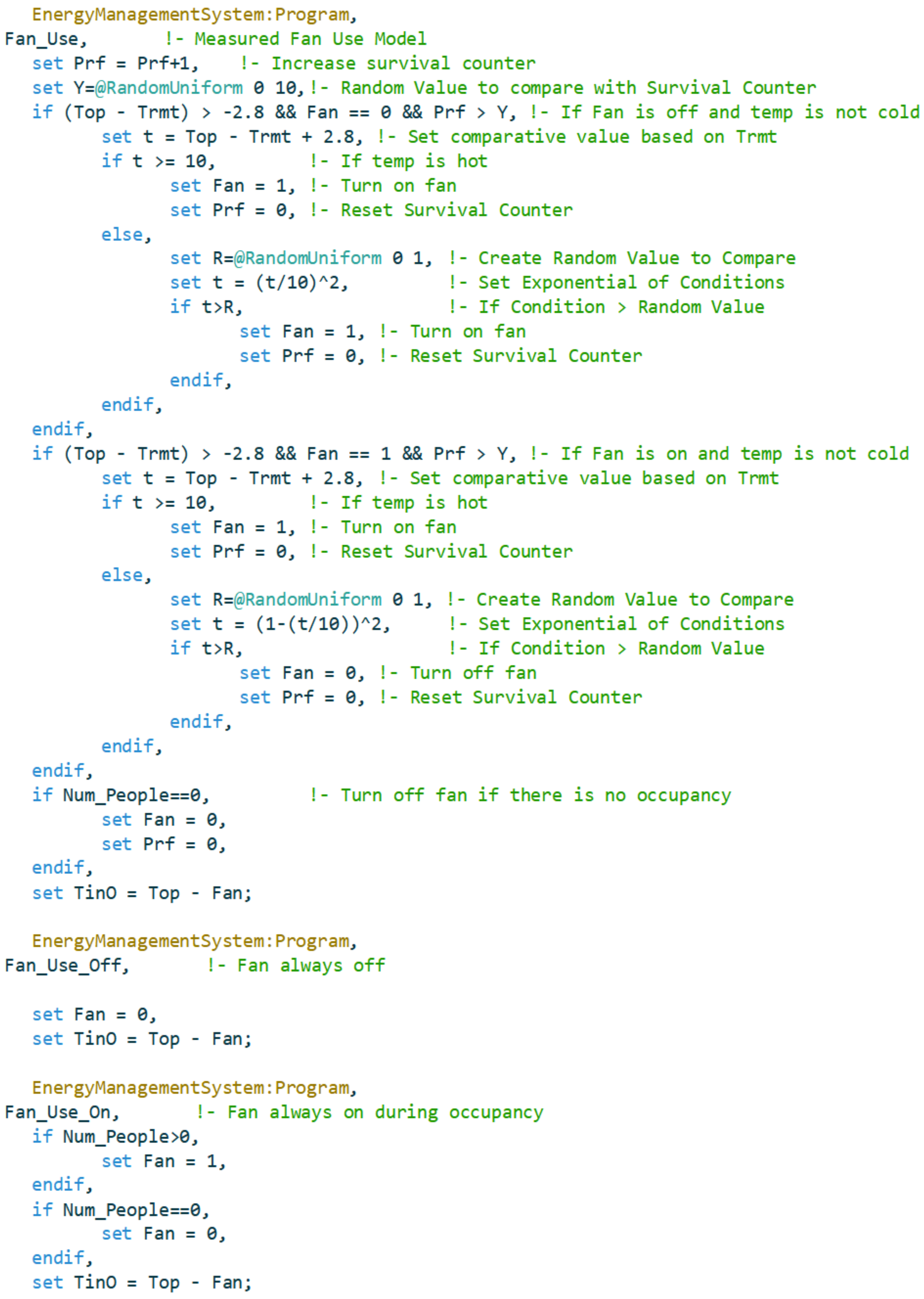
```
      EnergyManagementSystem:Program,
    Window_Haldi_2009_Off,       !- Window closed model

      set Window = 0;                   !- Window Always closed

      EnergyManagementSystem:Program,
    Window_Haldi_2009_On,       !- Window open model
      if Num_People>0,
            set Window = 1,             !- Window Always Open during occupancy
      endif,
      if Num_People==0,
            set Window = 0,             !- Window Closed without occupancy
      endif;

      EnergyManagementSystem:Program,
    Window_Haldi_2009_I,       !- Ideal window behavior model
      set Pr = Pr+1,                    !- Increase survival counter
      set X=@RandomUniform 0 10,!- Random Value to compare with Survival Counter
      set t = ((0.31*Trmt)+17.5),       !- Set comparative value based on Trmt
      if Tin > Tout && TinO > (t-3) && Tout > (t-3) && Pr > X, !- If warm inside and cooler
out
            set Window = 1,             !- Open Window
            set Pr = 0,          !- Reset Survival Counter
      elseif Tin < Tout && TinO < (t+3) && Tout < (t+3) && Pr > X, !- If cool inside and
warmer out
            set Window = 1,             !- Open Window
            set Pr = 0,    !- Reset Survival Counter
      elseif Pr > X,              !- If not
            set Window = 0,      !- Close Window
            set Pr = 0,    !- Reset Survival Counter
      endif,
      if Num_People==0 && Trmt > 22.2 && TinO > 22 && Pr > X, !- Open Window overnight when
warm
            set Window = 1,
            set Pr = 0,
      endif,
      if Trmt < 22 && Tin > Tout && Pr > X,   !- Close Windows when cold
            set Window = 0,
            set Pr = 0,
      endif;
```

Both Offices - Fan Use Models

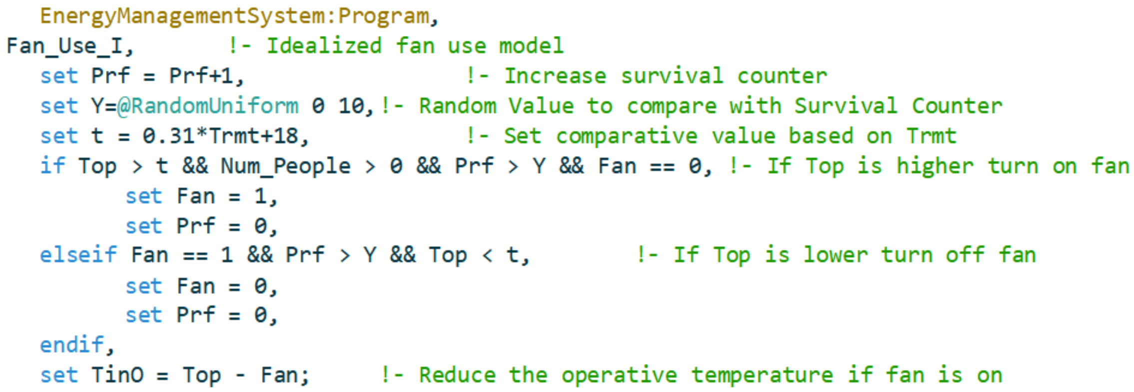


```
   EnergyManagementSystem:Program,
Fan_Use,        !- Measured Fan Use Model
   set Prf = Prf+1,     !- Increase survival counter
   set Y=@RandomUniform 0 10,!- Random Value to compare with Survival Counter
   if (Top - Trmt) > -2.8 && Fan == 0 && Prf > Y, !- If Fan is off and temp is not cold
         set t = Top - Trmt + 2.8, !- Set comparative value based on Trmt
         if t >= 10,         !- If temp is hot
               set Fan = 1, !- Turn on fan
               set Prf = 0, !- Reset Survival Counter
         else,
               set R=@RandomUniform 0 1, !- Create Random Value to Compare
               set t = (t/10)^2,         !- Set Exponential of Conditions
               if t>R,                   !- If Condition > Random Value
                     set Fan = 1, !- Turn on fan
                     set Prf = 0, !- Reset Survival Counter
               endif,
         endif,
   endif,
   if (Top - Trmt) > -2.8 && Fan == 1 && Prf > Y, !- If Fan is on and temp is not cold
         set t = Top - Trmt + 2.8, !- Set comparative value based on Trmt
         if t >= 10,         !- If temp is hot
               set Fan = 1, !- Turn on fan
               set Prf = 0, !- Reset Survival Counter
         else,
               set R=@RandomUniform 0 1, !- Create Random Value to Compare
               set t = (1-(t/10))^2,     !- Set Exponential of Conditions
               if t>R,                   !- If Condition > Random Value
                     set Fan = 0, !- Turn off fan
                     set Prf = 0, !- Reset Survival Counter
               endif,
         endif,
   endif,
   if Num_People==0,         !- Turn off fan if there is no occupancy
         set Fan = 0,
         set Prf = 0,
   endif,
   set TinO = Top - Fan;

   EnergyManagementSystem:Program,
Fan_Use_Off,       !- Fan always off

   set Fan = 0,
   set TinO = Top - Fan;

   EnergyManagementSystem:Program,
Fan_Use_On,       !- Fan always on during occupancy
   if Num_People>0,
         set Fan = 1,
   endif,
   if Num_People==0,
         set Fan = 0,
   endif,
   set TinO = Top - Fan;
```



```
  EnergyManagementSystem:Program,
Fan_Use_I,       !- Idealized fan use model
  set Prf = Prf+1,                 !- Increase survival counter
  set Y=@RandomUniform 0 10,!- Random Value to compare with Survival Counter
  set t = 0.31*Trmt+18,            !- Set comparative value based on Trmt
  if Top > t && Num_People > 0 && Prf > Y && Fan == 0, !- If Top is higher turn on fan
        set Fan = 1,
        set Prf = 0,
  elseif Fan == 1 && Prf > Y && Top < t,        !- If Top is lower turn off fan
        set Fan = 0,
        set Prf = 0,
  endif,
  set TinO = Top - Fan;      !- Reduce the operative temperature if fan is on
```