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Assessment of Natural Ventilation in a Case Study Building Using the Adaptive Thermal Comfort Model

Frederico Martins de Barros[1], Rodrigo Mora[1], Chris Flood[2]

[1] British Columbia Institute of Technology, Burnaby,
[2] Integrated Environmental Solutions (IES-VE), Vancouver,

Abstract: *The paper presents a natural ventilation assessment using field testing and whole building simulation model (WBSM) of a case study building located in Vancouver. The thermal comfort is evaluated using the adaptive thermal comfort (ASHRAE 55, 2013). The field testing includes the installation of an on-site weather station and sensors to monitor the indoor environment. The WBSM is used to analyze the impact of design features that compose the natural ventilation strategy in a sensitivity analysis. The design features analyzed are solar shading system, internal spaces connectivity, green roof, and a solar chimney. From the field testing, using the adaptive thermal comfort, it was found that for most spaces the natural ventilation was effectively delivering thermal comfort for the building occupants. The sensitivity analysis shows that for the case study building and Vancouver's climate there is not just one design feature that is substantially more effective than the others.*

Keywords: *natural ventilation, thermal comfort, adaptive model, building performance simulation*

INTRODUCTION

Natural ventilation is slowing gaining acceptance as a viable strategy to deliver satisfactory indoor environmental quality and cooling for spaces. Natural ventilation is a strategy to supply and remove air through the building openings by natural means, without the use of fans or another mechanical system. The airflow is caused by pressure differences between the building and its surrounding. In a few climates (i.e. with big temperature fluctuation, such as high temperatures at day and low at night-time), cooling strategies might also include pre-cooling building thermal mass by night-time ventilation to mitigate anticipated uncomfortably warm conditions during the coming day. However, the main drawback to natural ventilation is that mechanically ventilated buildings are significantly easier to design, control and verify. Mechanical ventilation is meant to typically overpower any natural or human forces that may create uncertainties and performance unreliability. The main conclusion from the study building is that adequate natural ventilative cooling for comfort is achieved through the careful integration of overall and local design strategies that consider adaptive possibilities for the representative occupants.

ADAPTIVE THERMAL COMFORT FOR NATURAL VENTILATION

One goal of a natural ventilation design is to maintain thermally comfortable indoor conditions without relying on mechanical cooling. In this paper, the main metric used to assess natural ventilation effectiveness is thermal comfort. The adaptive thermal comfort has been widely accepted as the most suitable thermal comfort model for naturally ventilated buildings. The adaptive model has been incorporated into widely used thermal comfort standards, such as ASHRAE Standard 55 (2013) and EN15251 (2007). The model has been developed based on numerous field studies in USA, Europe, and Asia.

According to Humphreys et al. (2001), the occupants of naturally ventilated buildings have a large range of tolerances to thermal comfort when compared to occupants in the mechanically ventilated building. Adaptive thermal comfort is a theory that suggests a human connection to the outdoors and the control over the immediate environment that allows them to adapt to a wider range of thermal conditions than is generally considered comfortable. The fundamental assumption of the adaptive approach is expressed by the adaptive principle: if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort. The development of the adaptive thermal comfort relies on the findings from thermal comfort surveys conducted by a number of researchers across the globe. It was founded that, for naturally ventilated buildings, the comfort temperatures is a function of outdoor air temperature.

Figure 1 presents the graph that represents the adaptive thermal comfort depending on the indoor operative temperature (t_o) and the prevailing mean daily outdoor air

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temperature ($\overline{t_{pma(out)}}$). The dark grey area in the graph represents the region where temperatures provide a thermal comfort for 90% of the occupants of the space, also known as the upper limit for thermal comfort. The light grey area (lower limit) represents the area where 80% of the occupants are comfortable with the conditions of the spaces.

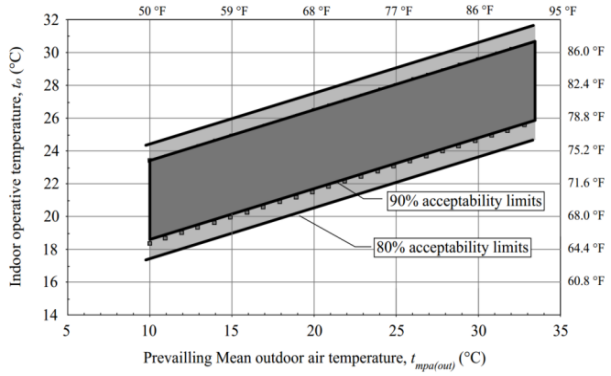

Figure 1: Acceptable operative temperature (t_o) ranges for natural ventilation (ASHRAE Standard 55, 2013)

Equation 1 and 2 mathematically represent the thermal comfort limits for 80% of acceptability.

$$Upper\ Limit = 0.31 \cdot \overline{t_{pma(out)}} + 21.3\ [°C] \quad (1)$$

$$Lower\ Limit = 0.31 \cdot \overline{t_{pma(out)}} + 14.3\ [°C] \quad (2)$$

According to ASHRAE Standard 55 (2013), the prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) shall be determined in accordance with the following:

- It shall be based on no fewer than seven and no more than 30 sequential days prior to the day in question;
- It shall be a simple arithmetic mean of all of the mean daily outdoor air temperature of all the sequential days in the previous point.

CASE STUDY BUILDING

The 1,780 m² (19,160 ft²) case study building is a one-storey landmark building with a design aimed to achieve net-zero energy through a variety of technologies including solar hot water, photovoltaic panels, geothermal boreholes and natural ventilation. The main motivation for using this building as a relevant case for natural ventilation assessment is that the building relies exclusively on natural ventilation to provide thermal comfort for its occupants during the summer. The building envelope is complex; it uses a number of different materials in different configurations. The envelope is mainly composed of a green roof, concrete walls, high-performance fenestration system, and concrete floor slabs.

The case study building is a multi-purpose single story visitor centre whose main purposes are for public education and rental spaces for private events, as well as to serve as access to an outdoor botanical garden. Table 1 shows the function of each space according to the ASHRAE 90.1 (2010) parameters.

Table 1: Names and space function of the case study building

Space function	Space name
Multipurpose	Flex 1 and 2, Great Hall
Atrium	Atrium
Retail	Garden Shop
Office	Garden Shop Office
Library	Library
Classroom	Classroom, Volunteer Room
Active Storage	-
Corridor	-
Food preparation	Food Service
WC	-
Mechanical or Electrical Room	-

The natural ventilation strategy in the building relies on a combination of cross-ventilation and buoyancy-driven ventilation. Cross-ventilation is achieved through automated operable windows positioned in all façade orientations. Buoyancy-driven ventilation draws air from the windows and drives it through high ceilings in all rooms, with a plenum space at the top of the rooms, and a central atrium. Moreover, at the top of the atrium, a solar chimney is designed to enhance the buoyancy-driven natural ventilation. In addition, the case study building presents a combination of design features that compose the overall natural ventilation strategy by improving the thermal comfort during its usage; these features are solar shading system, solar chimney, building's green roof, and the connectivity between the spaces. From our initial observations, we noted that proper connectivity between all spaces was lacking, as required for cross-ventilation. However, we later realized that initial airflow-links between spaces were removed due to privacy and noise concerns.

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BUILDING OCCUPANCY

In Table 2, the authors identified four occupancy groups, as the authors are not aware of any occupancy study for this building.

Table 2: Building occupancy groups

Occupancy group	Building occupancy time	Notes
1. Garden visitors	10 minutes to approximately 1 hour	Access the garden through the building, use the food service
2. Event users	Periods of 2 to 4 hours throughout the day	Rentals for events
3. Seasonal users	Whole days during summer weeks	Summer camps
4. Staff	Regular office hours throughout the year	Administrative and service staff

Theoretically, the adaptive thermal comfort model applies to all four groups in Table 2, except for the bulk of the occupants that use the building only as a transition to access the garden. However, each occupancy group has its own thermal expectations, consistent with the time of use of the building, which affect their thermal acceptability and satisfaction with the building thermal environment. Nevertheless, the building visitors are local people adapted to the local summer climate, and as long as opportunities for adaptation exist for occupants in each group to let them effectively create their own thermal preferences, the adaptive model should provide reasonably accurate comfort predictions. In this building, the following adaptive behaviours were observed: opening and closing of windows and doors, use of relaxed summer clothing outfits, and use of personal fans. The use of blinds was not necessary due to proper shading provided by the building design.

FIELD TESTING AND MONITORING

The field testing comprehends positioning sensors in the building to monitor its performance for a certain period of operation. The field testing was conducted from August 10th to August 25th of 2017. The factors analysed in the building monitoring are internal spaces air temperatures, relative humidity, CO_2 concentration rates, and open/close status of openings. In addition to that, in order to monitor the outdoor environment, a weather station was positioned on the building's roof. Table 3 sums up all the sensors used in the case study building.

Table 3: Equipment used for monitoring the case study building under natural ventilation

Sensors type	Measurement	Number of sensors
Hobo® data logger	Air temperature, relative humidity and CO_2 concentration	11
State sensors	Open and close status of the openings	16
Weather station	Outdoor air temperature, relative humidity, solar radiation, rain precipitation, wind speed and direction	1

State sensors were installed at the top corner of 16 doors. From these 16 doors, 4 were internal and 12 were external. During the summer period, the external doors are typically kept open during occupied hours to allow fresh cooler air into the internal spaces. The internal doors are also monitored in order to observe their influence in the overall natural ventilation performance. After all, with the opening of the internal doors, the connectivity between spaces is enhanced, creating larger airflow paths across the building by magnifying the cross-ventilation. The airflow through the solar chimney might also be increased due to the improvement in the internal connectivity.

The weather station positioned on the building roof is responsible to record the outdoor air temperature, relativity humidity, solar radiation, rain precipitation, and the wind speed and direction.

OUTDOOR ENVIRONMENT

The recorded weather data was collected during the summer in Vancouver, Canada. The maximum temperature recorded was 29.5 °C and the minimum was 11.9 °C, during the night-time. During the monitoring, the average outdoor air temperature in the occupied hours (from 10 AM to 9 PM) was 21.8 °C. In terms of solar gains, the recorded days presented considerable solar radiation. The peak value was 909 W/m² at 2 PM on August 24th. During the daily peak, solar radiation values were around 800 W/m². Figure 2 illustrates both solar radiation and outdoor air temperature.

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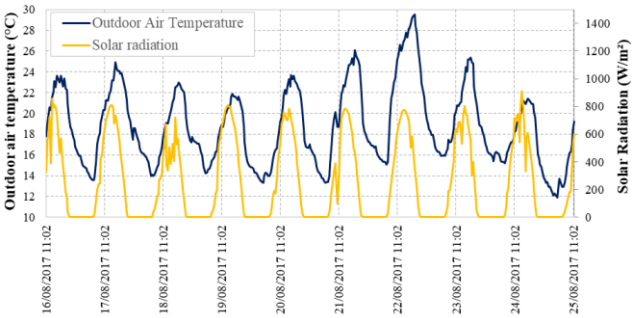

Figure 2: Outdoor air temperature and solar radiation recorded by the local weather station

A key aspect of natural ventilation is the wind. It is not possible to say that the recorded wind data is representative for the year-round wind behaviour on-site. Notwithstanding, this data indicates wind speeds and direction during the monitoring period. For the majority of the time, the wind direction was south-east, but north-west wind occasionally occurred. Figure 3 presents the wind frequency for the monitoring period.

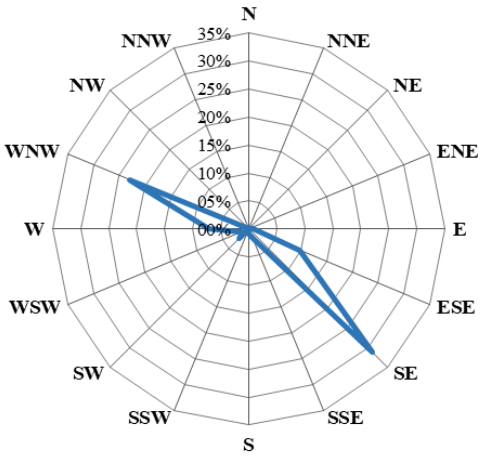

Figure 3: Wind-rose frequency from August 16th to August 25th

Regarding the wind speed, for the majority of the time, the wind speed was inexistent or below 0.5 m/s. Only 1% of the data reported wind speeds above 2 m/s. The local climate, terrain condition, and height of the weather station localized on the building's roof may explain the relatively lower wind speeds and limited wind direction. The whole wind speed distribution recorded by the local weather data is illustrated by Figure 4.

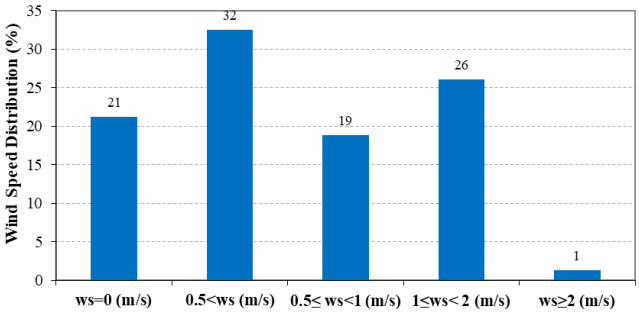

Figure 4: Wind speed distribution

INDOOR ENVIRONMENT

As a part of the indoor environment, internal air temperatures, CO_2 concentration rates, relative humidity, and windows and doors status (open and closed) were recorded. Table 4 summarizes the maximum, minimum and average temperatures recorded for the different spaces.

Table 4: Recorded temperatures at the field testing

	Max. Temp. (°C)	Min. Temp. (°C)	Avg. temp. (°C)
Atrium	28.9	22.3	24.8
Arrival hall	28.6	23.1	25.5
Classroom	28.4	23.7	25.4
Great hall	27.4	22.9	24.4
Flex 1	28.1	23.3	24.8
Flex 2	28.1	23.1	24.7
Food service	30.2	22.4	26.2
Garden shop	28.3	23.1	25.4
Gar. shop office	28.9	25.7	27.5
Library	27.2	23.4	24.9
Volunteer room	28.0	22.8	24.3

ADAPTIVE THERMAL COMFORT ANALYSIS

The metrics used to assess the thermal comfort are the aforementioned adaptive thermal comfort suggested by ASHRAE Standard 55 (2013) in association with the exceedance hours (*EH*), also presented by the same standard. The exceedance hours method (*EH* method) allows the quantification of the number of hours in which environmental conditions are outside the comfort zone requirements during the occupied hours in the period of interest. The comfort range adopted considers the

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acceptability of 80%. The calculation of the *EH* follows equation 3.

$$EH = \sum (H_{>upper} + H_{<lower}) \quad (3)$$

where,

$H_{>upper}$ = 1 if $t_{op} > t_{upper}$ and 0 otherwise;

$H_{<lower}$ = 1 if $t_{op} < t_{lower}$ and 0 otherwise;

t_{upper}: upper comfort range;

t_{lower}: lower comfort range.

$H_{>upper}$ and $H_{<lower}$ are discomfort hours outside the zone boundaries and the units are in hours. Although, the method proposed on the standard only quantify the total of discomfort hours, which were separated in cold discomfort hours and hot discomfort hours by the author. The reason behind that choice is that since natural ventilation is being evaluated in providing cooling for spaces, the analysis of hot discomfort range exclusively is more suitable for that application. Therefore, with that approach is possible to isolate the $H_{>upper}$ factor to serve as a comparative factor later to be used in the sensitivity analysis.

The prevailing mean daily outdoor air temperature ($\overline{t_{pma(out)}}$) was calculated using a linear average of the last 15 days temperatures, following the directions proposed by ASHRAE Standard 55 (2013). As the time steps used in the monitoring was every 5 minutes, for each time step there is a reading representing the space temperature for a given $\overline{t_{pma(out)}}$. The data used in the analysis is only related to the building occupied hours, which is from 10 AM to 9 PM at summer time. The same concept is applied to the *EH* calculation. Different from what is recommended by ASHRAE Standard 55 (2013), which uses the operative temperatures (t_{op}) in the adaptive thermal comfort approach, the spaces air temperatures were used in the analysis instead. This limitation was imposed by the building owners in order to avoid the intrusion to the building occupancy imposed by the instrumentation needed in order to measure the operative temperatures in all spaces. Notwithstanding, knowing the building aspects and characteristics is not expected a big discrepancy between the operative and spaces air temperature.

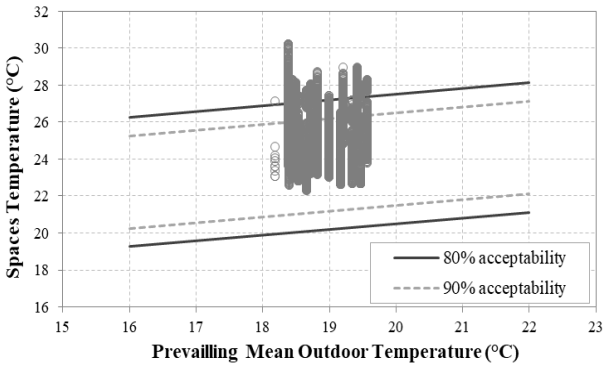
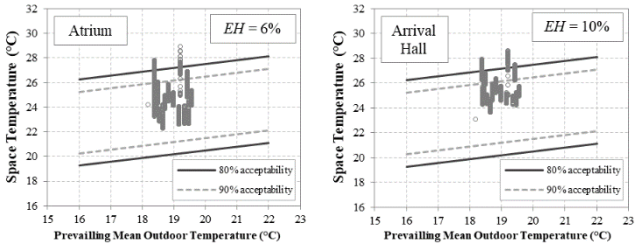


Figure 5: Adaptive thermal comfort analysis

Figure 5 shows that for most time the temperatures are within the thermal comfort range. However, there are points outside the comfort range. To observe what is happening in each space, the data illustrated in Figure 5 is broken down to show the comfort analysis for each individual room. The spaces are grouped based on their similarity and space function.

Figure 6 shows the adaptive thermal comfort applied to the atrium and arrival hall. Both spaces have transient characteristics in terms occupancy and a similar usage. For the atrium, during 6% of the time-space is not under comfort temperature, according to the adaptive thermal comfort. In the arrival hall, 10% of exceedance hours (*EH*) were observed during the field testing. The higher thermal discomfort of the arrival hall is possibly explained by the higher solar gains through the south face envelope, the doors located at the space are not always kept open, like both doors in the atrium. Moreover, the atrium also has the presence of the solar chimney.



a) Atrium b) Arrival hall

Figure 6: Adaptive thermal comfort applied to the Atrium and Arrival hall

The adaptive thermal comfort applied to the rental spaces are illustrated in Figure 7 (i.e. great hall, flex 1 and 2). For the majority of the time, the spaces are at comfortable temperatures. The great hall shows the best performance in terms of thermal comfort in comparison with other

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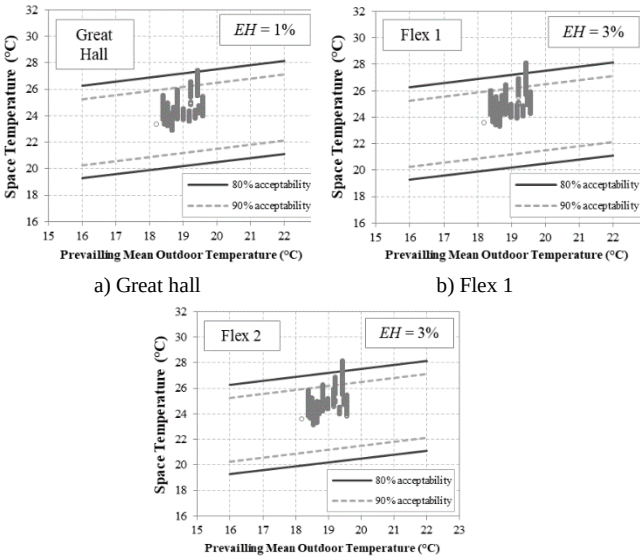
spaces. The 1% of *EH* in the great hall and the 3% in the Flex 1 and 2, is relative to only 1 and 5 hours, respectively. For that time, based on the CO_2 readings, there were no events happening in those spaces. Then, it is possible to assume that the rental spaces had comfortable temperatures during all the events held during the building testing and monitoring.



a) Great hall b) Flex 1

c) Flex 2

Figure 7: Adaptive thermal comfort applied to the rental spaces

Regarding the food service, Figure 8 shows the adaptive thermal comfort applied to that space. Different from the previous spaces, the food service presented uncomfortable temperatures for a substantial period of time, with *EH* of 23%. These numbers result from the high thermal gains generated by the kitchen and the data logger position.

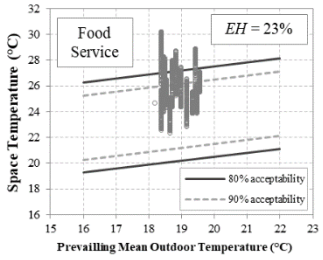
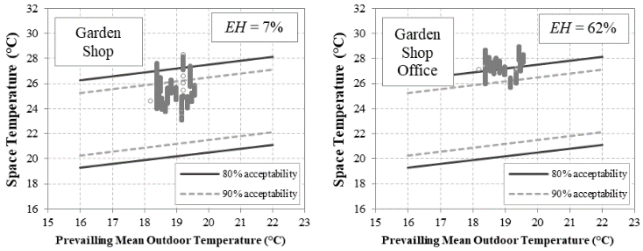


Figure 8: Adaptive thermal comfort applied to the Food service

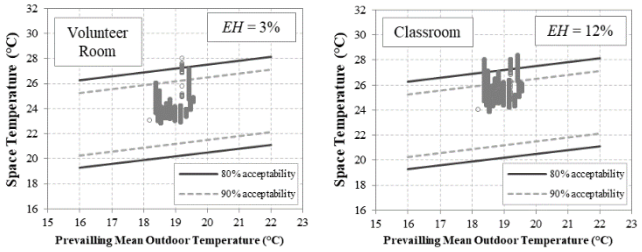
Figure 9 illustrates the adaptive thermal comfort applied to both Garden shop and its office. The Garden Shop presents a reasonable *EH* value of 7%, but the garden shop office shows an *EH* of 62%. The high value of the thermal discomfort at the office is caused by the lack of proper ventilation and ways to extract the heat from that space.



a) Garden shop b) Garden shop office

Figure 9: Adaptive thermal comfort applied to the Garden shop and Office

Both volunteer and classroom are rooms with similar usage, however, they are positioned at opposite sides in the building. Volunteer room is located in the south part of the building and the classroom in the north part. The high exposure to solar radiation in the south façade of the classroom may explain the higher thermal discomfort of that space in comparison with the volunteer room. The classroom showed a *EH* of 3% and the classroom a *EH* of 12%. Figure 10 shows the final results for both spaces.



a) Volunteer room b) Classroom

Figure 10: Adaptive thermal comfort applied to the Volunteer room and Classroom

During the monitoring, the library was the most comfortable space in the building. During the occupied time, the space temperatures were always within the comfortable temperature range. Figure 11 illustrates the final results for the adaptive comfort for the library.

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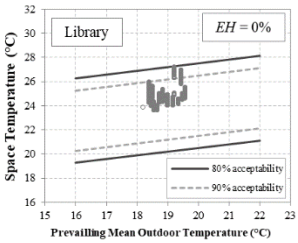

Figure 11: Adaptive thermal comfort applied to the Library

Table 5 summarizes the exceedance hours (*EH*) for the different spaces analyzed.

Table 5: Exceedance hours (EH) recorded at the field testing

	***EH* (%)**	***EH* (hrs.)**
Atrium	5.9	11
Arrival hall	9.8	18
Classroom	11.7	21
Great hall	0.8	1
Flex 1	2.9	5
Flex 2	3.0	5
Food service	22.9	41
Garden shop	7.4	13
Gar. Shop office	62.1	111
Library	0.0	0
Volunteer room	2.8	5
Avg. Spaces temp.	5.8	10

Apart from a couple of rooms (i.e. food service and garden shop office) that are clearly are overheating in the summer, it is possible to say that the natural ventilation is effectively delivering a thermal comfort for the indoor environment for the period when the monitoring was realized.

CASE STUDY'S NATURAL VENTILATION SENSITIVITY ANALYSIS

A sensitivity analysis is made in order to address how different design features are critical in the natural ventilation effectiveness. In order to do the analysis, a WBSM was developed and validated for the case study building. Martins de Barros (2017) presents the whole process and details of the WBSM development and validation. The software used was IES-VE. In the sensitivity analysis, the analyzed design features that compose the natural ventilation strategy are solar shading system, internal spaces connectivity, green roof, and a solar chimney. The analysis consists of a baseline simulation, which represents the optimum design for natural ventilation, in comparison with the simulation that has a modification on a specific design feature that composes the natural ventilation strategy.

Similar to the previous analysis, the metrics used to assess the thermal comfort is the adaptive thermal comfort suggested by ASHRAE Standard 55 (2013) in association with the exceedance hours (*EH*). The analysis uses only operative temperatures, as suggested by ASHRAE Standard 55 (2013). The *EH* is calculated for operative temperatures that are higher than the upper limit threshold. Temperatures below the lower limit of thermal discomfort are not considered in the analysis. In other words, when the room is colder than the adaptive thermal comfort suggests, that value was not considered in the final *EH* calculation. After all, the natural ventilation is being evaluated in its capacity to provide cooling for the spaces. The simulations were all relative to the months of July and August, the warmest period in Vancouver.

The baseline model is a representation of the optimum design for natural ventilation, with all the features that could be considered as good design practices, in theory. In that optimum design, the building has improved spaces connectivity, solar shading system, green roof, and a solar chimney. The alternative simulation represents a model with a certain feature removed. The current case study building has all the design strategies applied apart from the improved spaces connectivity. Table 6 summarizes how the simulations are distributed

Table 6: Sensitivity analysis simulations

Factor analyzed	Baseline	Alternative simulation
Solar shading system	Optimum Design	No Shading System
Spaces connectivity	Optimum Design	Actual Building (Poor Connectivity)
Green roof	Optimum Design	No Green Roof (roof from ASHRAE 90.1)
Solar chimney	Optimum Design	No Solar Chimney

SOLAR SHADING SYSTEM

The case study has a robust solar shading system. In the sensitivity analysis, the baseline model represents the current status of the building and the other simulation represents the building with no shading system at all. The results showed that, as expected, spaces exposed to the south were the one with the drastic drop in the thermal comfort. Considering the whole building, the baseline

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simulation has an *EH* of 2.39% and the simulation without the solar shading has 3.82%.

INTERNAL SPACE CONNECTIVITY

Regards the internal spaces connectivity, the baseline WBSM presented the optimum configuration, with internal grilles connecting spaces that have openings to the north and south corridors, and the walls limited to certain height, above that height the rooms are all connected in a great plenum space that allows the warm air to flow across the building until being exhausted by the solar chimney. In the other simulation, which represents the current building, key spaces have no connection between each other and the rest of the building. There are no grilles or flow paths that allow the air to flow from these spaces to the rest of the building, acting like single-sided ventilated spaces.

The results show that for the overall building, the *EH* is 2.63% for the model with reduced spaces connectivity and 2.39% for the baseline.

GREEN ROOF

The baseline WBSM presents the building with the green roof. The simulation with no green roof uses a standard roof assembly as suggested by ASHRAE 90.1 (2010) for Vancouver's climate zone 5. This roof assembly's thermal performance and thermal mass are lower than those of the original green roof.

The results indicate that for all spaces the green roof slightly improves the natural ventilation effectiveness. For the whole building, the *EH* is 2.39% for the baseline and 2.80% for the simulation without the green roof.

SOLAR CHIMNEY

The case study building has a solar chimney, which is claimed to be one of the main features in the building's natural ventilation strategy. The baseline simulation shows the normal building with the solar chimney. In the other simulation, there is no solar chimney on the building's roof, just a flat continuity of the roof.

After the analysis, it is shown that the presence of the solar chimney improves the natural ventilation effectiveness for most spaces. In the overall building, the *EH* was 2.39% for the baseline and 2.71% for the simulation without the solar chimney. In the simulation without the solar chimney, the warm air is trapped at the plenum, affecting the spaces' thermal performance by decreasing the buoyancy-driven ventilation from the other spaces.

SENSITIVITY ANALYSIS RESULTS AND COMPARISON

Firstly, as expected, all the design features analyzed to improve the natural ventilation effectiveness by cooling the spaces. Between the factors analysed, the more effective strategy is the building's solar shading system. The second more effective factor is the green roof, followed by the building's solar chimney in third and by the internal spaces connectivity in forth. However, the differences between the green roof, solar chimney and the internal connectivity are minimal. Differently from the shading system that showed substantially better results than the other features. Table 7 presents a summary of the results calculated in the analysis.

Table 7: Sensitivity analysis simulations

	***EH* (%)**	***EH* (HR.)**	**Decrease in thermal comfort in comparison with the baseline (%)**
Baseline	2.4	212	-
No solar shading system	3.8	339	59.9
No green roof	2.8	248	17.0
No solar chimney	2.7	240	13.2
Reduced internal spaces connection	2.6	233	9.9

Figure 12 illustrates the final results of the sensitivity analysis.

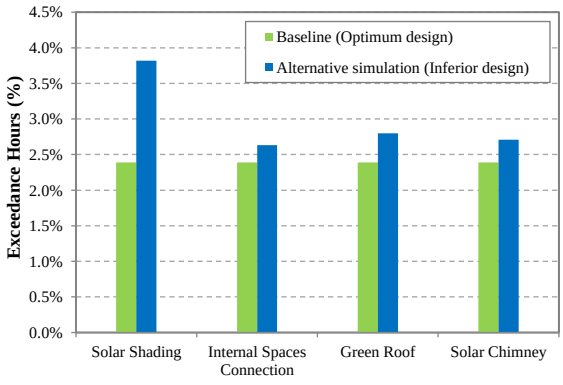

Figure 12: Sensitivity analysis results

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The results show the complexity of the natural ventilation strategy, which is composed of a number of different features. Aside from the internal spaces connectivity, all the other features are key architectural elements, which not necessarily is the responsibility of the building designer. This endorses the idea of having a cooperative team working together in order to have an efficient building, especially when involving a naturally ventilated building.

CONCLUSION

Regarding the field testing performed in the case study, it was shown that for most spaces the temperature was in the comfort range according to the adaptive thermal comfort. The most comfortable space is the library, followed by the rental spaces (great hall, flex 1 and 2) and volunteer room. The atrium, garden shop, arrival hall and classroom presented temperatures outside the thermal comfort range for the fair amount of time, with *EH* varying from 6 to 12% of the occupied hours. For two spaces, however, the amount of time that the spaces were outside the comfort range was too drastic and adjustments need to be considered. The food service showed an *EH* of 23% and the garden shop office an *EH* of 62%. It is possible to assume that the data sample was not significant for the whole summer operation but it indicates that the alternative measures need to be taken in order to provide comfort for these spaces during the summer.

On the strategies that compose the natural ventilation in the case study building, it is shown that the more effective strategy in delivering thermal comfort is provided by the solar shading system. Alongside that element, the green roof, solar chimney, and internal spaces connectivity come in that order of importance. The influence of the solar shading in the thermal comfort is perceived in all spaces but is more evident in rooms that are exposed to solar radiation, in special rooms with south face fenestration. On the green roof influence, this feature affects all spaces in a minor amount. The solar chimney showed an influence in the overall building's thermal comfort. Its influence was not substantially observed in spaces directly connected with the chimney, showing that the solar chimney is effectively drawing the warmer air from all different spaces and exhausting it through its openings. The influence of spaces connectivity slightly improve the natural ventilation effectiveness and was more evident in a few rooms. Given the the use of personal fans was observed in various spaces, it is recommended that future designs should contemplate the integration of ceiling fans to enhance ventilative cooling and improve thermal comfort.

In conclusion, the effectiveness of natural ventilation is affected by the architectural design; but from the case study building, for Vancouver's mild summer season, there is no drastic influence of one specific design feature in the overall effectiveness of natural ventilation. For this case study, the major design feature was the solar shading system. However, it is important to put the results of this study in its climate context. Therefore, it can be hypothesized that the results from the sensitivity analyses would have been more dramatic in a hot humid climate. In summary, the effectiveness of natural ventilation is a result of an integrated effort of a number of design features.

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