

Predicting the Effectiveness of Wind-Driven Natural Ventilation Strategy For Interactive Building Design

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Abstract

While an early stage design is highly likely to be changed, conducting natural ventilation simulations for various design alternatives can be challenging given the considerable effort required to run one simulation. The goal of this study, therefore, is to provide useful feedback for those who conduct energy simulations with an interest in natural ventilation. This study uses existing simulation software and 3D modeling tools to inform users of the natural ventilation effectiveness (NVE) of their design. The study first introduces the process of the simulation, and then demonstrates the integrated 3D modeling in *Rhinoceros*. The proposed simulation yields the values and maps of the NVE, and helps decide possible design alterations.

Introduction

Tools for natural ventilation prediction

The following tools have been devised to provide natural ventilation information during the design process:

- Site and climate analysis tools
- Airflow network (AFN) models
- Computational fluid dynamics (CFD)

Site and climate analysis tools consider local climate and customized thermal comfort criteria. The tools help designers to determine the suitability of adopting natural ventilation as a design strategy, and suggest the appropriate ventilation strategy. *Climate Consultant* by Milne, Liggett and Al-Shaali (2007) analyses a weather file and suggests design strategies per the thermal comfort model of one's choice. *Climate Suitability Tool*, created by Emmerich, Polidoro and Axley (2011), yields the required ventilation rate and the effectiveness of night cooling under a given internal heat load.

While the tools mentioned above do not require specific building designs, airflow network (AFN) models can be used to predict natural ventilation when a preliminary building design is available. AFN assumes that the air is well mixed within a zone, and uses the bulk airflow to calculate the interzonal airflow movement. Therefore, it takes a relatively short time to calculate than CFD.

CoolVent, developed by MIT researchers, is an example that employs the AFN model. It allows the natural ventilation prediction for certain types of strategies, including single-sided and cross ventilation, single-sided atrium, and central atrium ventilation. With transient and steady-state simulation options, it lets users explore key design parameters for natural ventilation, such as height of the chimney, opening areas, and building dimensions (Menchaca and Glicksman, 2008).

Computational fluid dynamics (CFD) simulations can evaluate natural ventilation in a greatly detailed way, but require a significant amount of time and a high degree of expertise. To overcome this challenge, researchers have suggested various approaches to reduce the time and complexity of simulations. Bartak et. al. (2002), Tan and Glicksman (2005), Wang and Chen (2007), Wang and Wong (2009), Zhang et. al. (2013), Yi and Feng (2013), and Yan, Malkawi, and Chen (2015) presented methodologies for integrating CFD and building energy simulation for natural ventilation. This coupling approach was aimed to reduce CFD simulation times and to enhance the accuracy of energy simulations. Other than coupling, Jin, Zuo and Chen (2013) validated Fast Fluid Dynamics (FFD) as an alternative to CFD. They demonstrated that FFD is an adequate tool for natural ventilation and is faster than conventional CFD tools. Yoon, Oshitani and Ando (2014) proposed an automated CFD to streamline the complex simulation process, and made use of BIM technology to shorten simulation preparation time.

With these efforts, solutions with acceptable accuracy within a reasonable timeline have become possible. However, less attention has been paid to the dynamic, or parametric, design process for natural ventilation.

Parametric simulation for natural ventilation

A preliminary design is bound to change many times as it is developed through interdisciplinary teams of professionals, including architects, engineers, builders and/or clients. When it is necessary to check the energy performance of many design alternatives, a parametric simulation approach can be a useful choice. In fact, recent studies done by Ercan and Elias (2015), Anton and Tănase

(2016), Raimondi et. al. (2016), and Qingsong and Fukuda (2016) have shown that the parametric design approach contributes to better informed architecture during the early design stage.

Ladybug, a plugin tool for *Rhinoceros* introduced by Roudsari and Pak (2013) and the successive plugin tool *Honeybee* are good examples of performance-based parametric design. With these tools, parametric approaches for daylighting and energy analysis are getting refined. However, parametric studies for natural ventilation that respond to the fast-changing nature of design have not as actively been investigated yet. In fact, a conventional way of considering natural ventilation in energy simulation tools uses a calculated air change rate per hour (ACH) or pressure coefficients (C_p 's) to simulate the building energy and shows the resultant temperature and energy loads. But it does not give information as to how much ACH is required to reduce the cooling energy loads for the given design or what could be done to increase or decrease the ACH accordingly as illustrated in Figure 1. For example, if the input ACH was calculated from the wind environment, it should be recalculated when the design changes. Since an ACH depends on the volume of a room, one must carefully revise the input settings of the energy simulation each time the design is modified. This may be a problem when a design is rigorously developed.

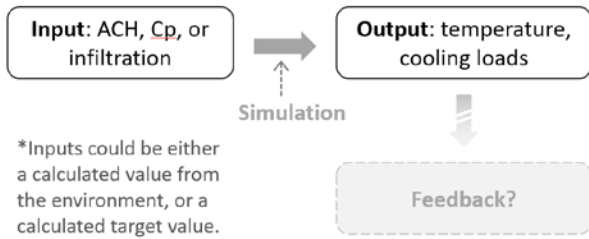


Figure 1. Natural ventilation component in EnergyPlus: Conventional method

To give and take feedback among consultants and architects, a method that can quickly and effectively inform the degree of natural ventilation usability needs to be introduced. Since CFD is not the best option for parametrization due to the complexity and the significant time it requires, an AFN model from *EnergyPlus* will be used as an engine of energy analysis. *Rhinoceros* is used as a 3D modeler, *Grasshopper* is used for parametrization, and *Ladybug* and *Honeybee* are used as plugins which connect to *EnergyPlus* in *Grasshopper*.

Scope

Two major driving forces for natural ventilation are wind and buoyancy, but *EnergyPlus* cannot model temperature distribution within a zone when the buoyancy effect is expected (Wang & Chen, 2008). Since this paper uses the AFN model in *EnergyPlus*, the parametrization will mainly focus on the natural ventilation occurred from the

external wind environment. We leave the implementation of buoyancy-driven ventilation as a next research topic.

Calculation Procedure

As indicated in Figures 2 and 3, the proposed method requires the input ACH calculated from the given environment, and then the simulation yields the required ACH that would offset the cooling load. The ACH required to offset the cooling load can be calculated by obtaining the cooling load with mechanical systems within the energy simulation. The ratio of input and output could be simply expressed to indicate whether the input ACH is sufficient to be used as a cooling source. Further instructions will be provided in the next few sections.

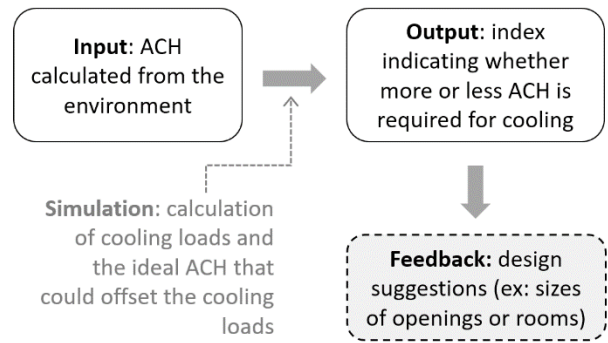


Figure 2. Natural ventilation component in EnergyPlus: Proposed method

Minimum airflow rate required as per ANSI/ASHRAE Standard

If a building uses natural ventilation, the airflow rate from natural ventilation should satisfy the minimum airflow outlined in ANSI/ASHRAE Standard 62.1. The minimum outdoor airflow required per zone per person, Q_{bz} , is determined by the Eq. (1) (ASHRAE, 2013):

$$Q_{bz} = R_p P_z + R_a A_z \quad (1)$$

where R_p is outdoor airflow rate required per person, P_z is the largest number of people expected to occupy the zone during typical usage, R_a is outdoor airflow rate required per unit area, and A_z is the net occupiable floor area of the zone. Now, Q_{bz} can be converted into air change rate per hour (ACH) by Eq. (2) in SI units:

$$ACH_{min} = 3600 Q_{bz} / V \quad (2)$$

where ACH_{min} is the minimum ACH and V is the volume of the room. Because ACH values can be directly used in energy modeling, this conversion is useful for the next step.

Cooling loads from energy modeling

Without cooling, the indoor temperature is often higher than outdoor temperature due to heat gains from solar radiation, conduction, and heat generation (CIBSE, 2005). To make the indoor temperature comfortable, i.e., to lower the indoor temperature (T_{in}) to the comfort

temperature ($T_{comfort}$), a certain amount of heat has to be removed. The heat rate that needs to be removed by natural ventilation can be expressed as in (3),

$$\dot{q} = \rho c Q (T_{in} - T_{comfort}) \quad (3)$$

where \dot{q} is heat rate in kJ/s , ρ is density of air in kg/m^3 , c is specific heat capacity of air in $\text{kJ/kg-}^\circ\text{C}$, and Q is

volumetric airflow rate in m^3/s . The T_{in} results from the solar radiation, internal heat gain, conduction through building materials, and more. The accumulative heat to remove for an hour—namely the cooling loads, q , in kWh —can be obtained through energy simulation.

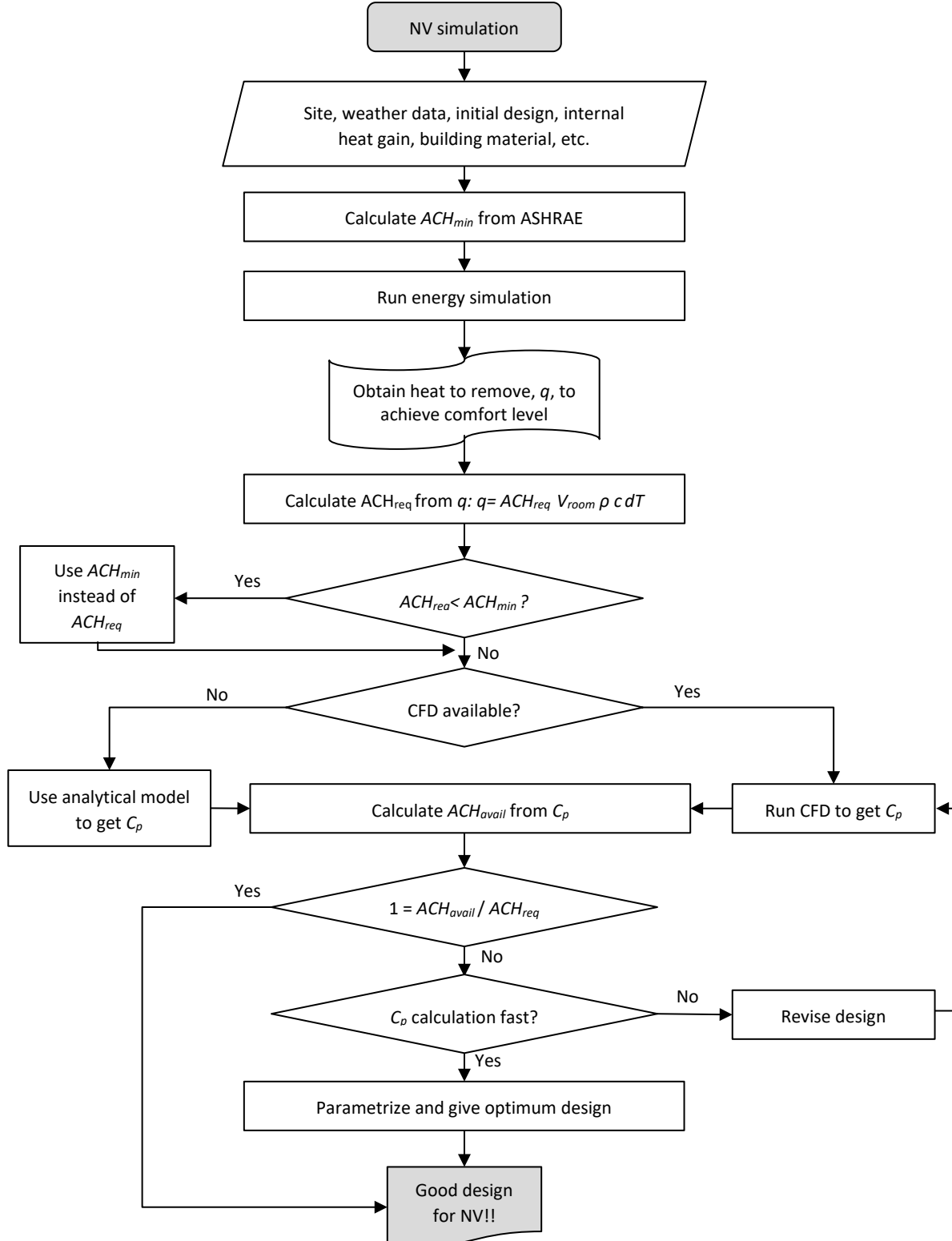


Figure 3. Suggested flowchart of natural ventilation evaluation during the design development phase.

The airflow rate, Q

To evaluate how much the wind-driven natural ventilation can reduce the cooling load, it is necessary to compare the required airflow rate, Q_{req} , and the available airflow rate at the site, Q_{avail} . Since \dot{q} in (3) is the heat rate that needs to be removed by natural ventilation, then Q_{req} needed to achieve the target temperature can be calculated as in (4):

$$Q_{req} = \dot{q} / \{\rho c (T_{in} - T_{out})\} \quad (4)$$

Here, $T_{comfort}$ can be used instead of T_{in} , because it assumes that the interior temperature is maintained to the comfort level. Assuming so would mitigate the needs of applying hourly boundary conditions of heat fluxes that would otherwise have depended on the previous conditions. The assumption implies that when natural ventilation is not sufficient for cooling, occupants would rely on mechanical systems to meet the comfort level. Now, Q_{req} can be converted to the required ACH, ACH_{req} , by (5) with a volume of the room, V .

$$ACH_{req} = 3600 Q_{req} / V \quad (5)$$

To find out whether the wind-driven natural ventilation can supply enough airflow, Q_{req} , the available airflow rate, Q_{avail} , needs to be calculated. The Q_{avail} depends on pressure coefficients of wind (C_p) at windows, an area of a window (A), a discharge coefficient of window (C_d) and wind velocity (v), and their relationship is expressed in (6). As was in (5), the Q_{avail} can be easily converted into ACH_{avail} .

$$Q_{avail} = A C_d v \sqrt{\Delta C_p} \quad (6)$$

The term $A C_d$ can be directly referred from the opening configuration. However, the rest of the terms $v \sqrt{\Delta C_p}$ should be further investigated to yield Q_{avail} .

Local wind speed, v

The wind velocity (v) in Eq. (6) is not vertically constant, and changes with height from the ground. Per ASHRAE Handbook of Fundamentals (2009), the local wind speed at the height of H , v_H , can be calculated as in (7),

$$v_H = v_{met} \left(\frac{\delta_{met}}{H_{met}} \right)^{a_{met}} \left(\frac{H}{\delta} \right)^a \quad (7)$$

where v_{met} is the velocity an anemometer measures at the height of H_{met} . The exponent a and the layer thickness δ are determined by the characteristic of a terrain.

Pressure coefficient, C_p

Inside of the square root in Eq. (6) is the difference in pressure coefficients at two opening surfaces, ΔC_p . This parameter plays a pivotal role in wind-driven natural ventilation calculations. The value depends on many conditions: the incident wind angle to the building surface, the vertical and the horizontal distances from the building edge to the opening, the complexity of building design, and the surrounding environments are some of the

major parameters that determine the C_p . While the accurate value of C_p is challenging to get, Cóstola, Blocken, & Hensen (2009) reviewed several sources to obtain the C_p values: primary sources including wind tunnel measurements and CFD, and secondary sources including, databases and analytical models. According to the authors, the most commonly used sources in building simulation are C_p databases from AIVC or ASHRAE handbook, and the analytical models such as a model suggested by Swami and Chandra (1988) and $CpCalc+$ by Grosso (1992) are rarely used. The primary sources tend to provide more accurate information albeit costly.

For the implementation purpose, the study uses the model suggested by Swami and Chandra. Their model provides two C_p equations for low-rise and high-rise buildings. Per their model, the C_p equation for a rectangular low-rise building is given as in (8),

$$\begin{aligned} C_{p,lowrise} = & 0.6 \cdot \ln(1.248 - 0.703 \cdot \sin(\theta/2)) \\ & - 1.175 \cdot \sin^2(\theta) + 0.131 \\ & \cdot \sin^3(2\theta \cdot G) + 0.769 \\ & \cdot \cos(\theta/2) + 0.071 \cdot G^2 \\ & \cdot \sin^2(\theta/2) + 0.717 \\ & \cdot \cos^2(\theta/2) \end{aligned} \quad (8)$$

where θ is defined as “the angle between the wind direction and the outward normal of the wall under consideration,” S as “the ratio of the width of the wall under consideration to the width of the adjacent wall,” and G as the natural log of S .

Also from the same model, the equation of C_p for each window on high-rise buildings as expressed as in (9),

$$\begin{aligned} C_{p,highrise} = & 0.068 - 0.839 \cdot \theta + 1.733 \\ & \cdot \cos(2\theta) - 1.556 \cdot ZH \\ & \cdot \sin(\theta) \cdot S^{0.169} - 0.922 \\ & \cdot \cos(2\theta) \cdot S^{0.279} + 0.344 \\ & \cdot \sin(2\theta) - 0.801 \cdot ZH \\ & \cdot \cos(\theta) + 1.118 \cdot \cos(Xr) \\ & - 0.961 \cdot \cos(Xr \cdot \theta) \cdot S^{0.245} \\ & + 2.515 \cdot ZH \cdot \sin(\theta) \\ & + 0.399 \cdot Xr \cdot \sin(\theta) \\ & - 0.431 \cdot XL + 0.046 \\ & \cdot \cos(Xr) \cdot S^{0.85} \end{aligned} \quad (9)$$

where the length ratio XL is defined as “the ratio of the horizontal distance of the point from the edge of the wall to the length of the wall,” the height ratio ZH is defined as “the ratio of the distance of the point from the ground to the height of the wall,” and $Xr = (XL - 0.5)/0.5$.

Although this paper uses the values calculated from the above equations, if one knows the C_p values from the wind tunnel tests and CFD simulations, the values can also be implemented in this parametrization.

The output, NVE_{wind}

Finally, the result of the simulation will be output as a ratio of Q_{avail} to Q_{req} , this index will be shown in the 3D model, and be called ‘wind-driven natural ventilation

effectiveness (NVE_{wind})' for convenience. The NVE_{wind} value with 1 indicating that the wind-driven ventilation can be effectively used as a cooling source, and 0 being no wind-driven ventilation available.

3D Implementation with Case Study

Modeling description

The calculations can be done in combination with energy modeling tool, 3D modeling tool and plugins, customized scripts and C_p resources as described in Figure 4.

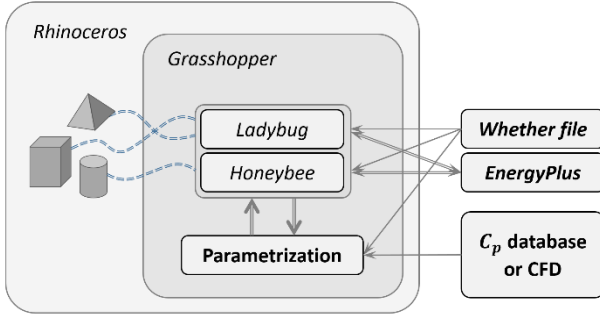


Figure 4. Procedure to Evaluate Natural Ventilation Effectiveness in Building Design

This section develops a parametrized system for the wind-driven natural ventilation in *Rhino*. It utilizes existing energy modeling plug-ins, *Ladybug* and *Honeybee*, to integrate the simulation process described in the previous section. A one-storey office building is modeled and examined for case study.

Geometry

A simple box of $5 \times 5 \times 4$ (m^3) is created to test the calculation. For an easy manipulation, the geometry is parametrized using *Grasshopper* components, by which its sizes of width and height, and the window location are parametrized as shown in Figure 5. The two windows are built on two adjacent sides (east and south) of facades with the dimension of $1 \times 1 \times 1$ (m^3), whose center is at 1.5m from the ground and 2.5m from the lateral boundaries of the building. The geometry is linked to *Honeybee* components to convert these surfaces into building components (floor, roof and walls, etc.).

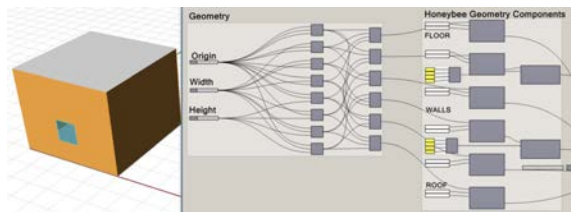


Figure 5. Geometry created in Grasshopper

Energy simulation

Once the *Honeybee* components are ready, energy simulation is run, and the hourly cooling loads during the designated time can be obtained. $15W/m^2$ of equipment load, $10 W/m^2$ of lighting load, $0.0004 m^3/s-person-m^2$ of infiltration rate, and $0.1 ppl/m^2$ of occupant density were

assumed. For this case study, the analysis is based at Boston, MA, and for the time of May 15th - Oct 15th.

ACH_{req}

The hourly temperature difference ($T_{comfort} - T_{out}$) from weather data and the hourly cooling load from energy simulation are then parsed and connected to the ACH_{req} calculation component.

When $T_{comfort} \leq T_{out}$, meaning that no cooling effect is available by exterior air, the ACH_{req} is adjusted to 9999999 to avoid a numerical error. The ACH_{req} is once again adjusted by comparing the minimum airflow rate explained in Eq. (1-2): if $ACH_{req} < ACH_{min}$, the ACH_{req} is replaced with ACH_{min} .

C_p and ACH_{avail}

Since this building is a one-storey building, Eq. (8) is coded as a function within *Grasshopper*. The parsed weather data including wind direction and velocity from *Ladybug* are called to yield C_p values at two openings. When $T_{comfort} \leq T_{out}$, meaning that cooling through the natural ventilation is not possible, the ACH_{avail} is set to zero.

NVE_{wind}

As mentioned in the previous section, the ratio of ACH_{avail} to ACH_{req} is calculated. This ratio is the NVE_{wind} of a certain hour in a day. Since the analysis period is May to October, the individual NVE_{wind} values are accumulated ($NVE_{wind(may-oct)}$) and divided by 3696 hours of the analysis period as in (10). A value bigger than 1 is regarded 1.

$$NVE_{wind(may-oct)} = \frac{\sum(ACH_{avail}/ACH_{req})}{3696} \quad (10)$$

With this accumulated NVE_{wind} for the building, several options can be tested to see how this configuration influences the effectiveness of the wind-driven natural ventilation. One may choose to change the location of the openings, size of the openings, or the volume of the zone. For this purpose, six more configurations are tested as listed in Table 1. Windows are located either adjacent or opposite sides, operable window areas are 0.5 or 0.25 (m^2), and the occupied room volume are $5 \times 5 \times 4$ or $10 \times 10 \times 4$ (m^3).

Table 1: Configurations of test cases

	Windows location	Operable window area (m^2)	Room volume (m^3)
Case 0	E,S	0.5	$5 \times 5 \times 4$
Case 1	N,S	0.5	$5 \times 5 \times 4$
Case 2	E,S	0.25	$5 \times 5 \times 4$
Case 3	E,S	0.5	$10 \times 10 \times 4$
Case 4	N,S	0.25	$5 \times 5 \times 4$
Case 5	N,S	0.5	$10 \times 10 \times 4$
Case 6	E,S	0.25	$10 \times 10 \times 4$

Windows for Case 1 are facing the south and the north, the sizes of windows for Case 2 is half of the Case 0, and the width and depth of the Case 3 are double the Case 0. Case 4 has south and north windows and smaller openings, Case 5 has south and north windows and larger room, and Case 6 has smaller openings and larger room.

Results

The natural ventilation analysis for a simple building has been conducted by calculating heat balance equations associated with ACH and by utilizing existing 3D modeling, energy modeling and parametrization tools. After the initial calculation is done, some parameters have been modified to learn the impacts of each parameter. Table 2 shows the results of all seven cases, and Figure 6 shows the NVE_{wind} maps of Case 0 and Case 6, which show the best and the worst performance, respectively. It reflects that natural ventilation effectiveness can vary by building design even under the same climate.

Table 2: The accumulated NVE_{wind} of test cases

	$NVE_{wind}(may-oct)$		$NVE_{wind}(may-oct)$
Case 0	0.736	-	-
Case 1	0.710	Case 4	0.689
Case 2	0.702	Case 5	0.675
Case 3	0.687	Case 6	0.598

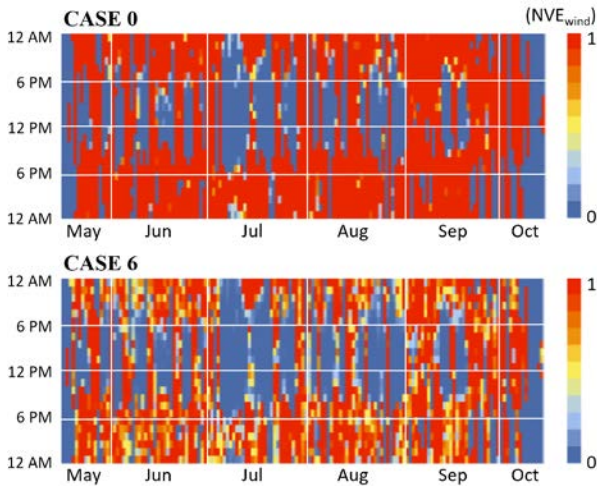


Figure 6. NVE_{wind} maps of Case 0 (top) and Case 6 (bottom)

As a reference, Case 0 is run for the entire year from January to December under three different climate zones: Boston, MA; Dallas, TX; and Santa Monica, CA. The results are shown in Figure 7. Note that the maps represent not only the climate of the site but also the building design that has been given. Santa Monica has shown the largest potential for this design. The unavailability of natural ventilation in Boston and Dallas mainly attribute to their cold winter and hot summer, respectively.

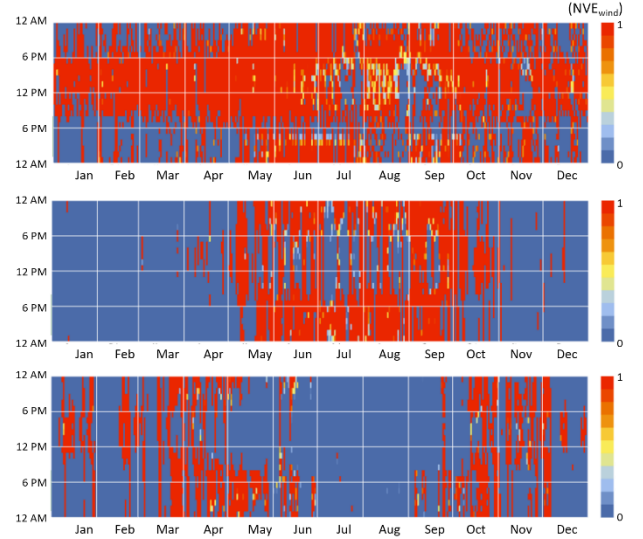


Figure 7 Annual NVE_{wind} maps of the test building in and Santa Monica, CA (top), Boston, MA (middle), Dallas, TX (bottom)

The proposed method may extend its feature to suggest several options depending on user's criteria as shown in Figure 8.

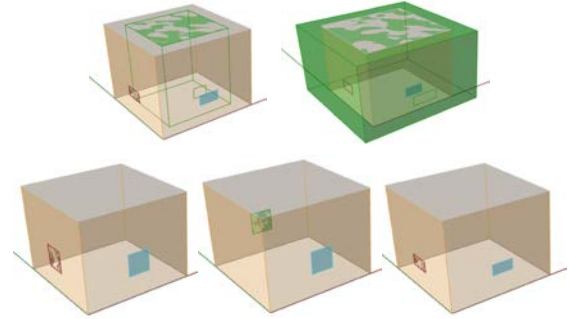


Figure 8. Possible suggestions from this study

Conclusion and Discussions

The proposed study is conducted to facilitate the consideration of natural ventilation during the design development stage, an early to intermediate design phase where a quick method of performance prediction is necessary, yet the analysis has to be specific enough to provide design feedback.

The study identifies the cooling load, given the building materials, weather conditions, internal heat loads and occupancy schedule set through an energy modeling tool, to determine the required ACH. It also finds external wind condition either by C_p database, C_p formulas, or CFD when available, to determine the available ACH at the site. It then compares the required ACH and available ACH, and yields either an instantaneous or an accumulated NVE_{wind} metric.

The motivation of this study was to bridge the gap of the modeling process between the initial design stage and the final stage. The primary site evaluation stage investigates the potential of the natural ventilation without building

information, and the finishing phase explores the details with advanced methods including measurements, CFD, or wind tunnel experiments.

For the intermediate design phase, this parametrized natural ventilation analysis takes users' own geometry in a commonly used 3D modeling tool. Its benefits come from the following facts:

1. Designers can use one model for energy simulation and natural ventilation prediction.
2. Natural ventilation potential prediction is tailored to the given building design.
3. It uses energy simulation results and weather files, so the calculation is faster than CFD or physical models.
4. The NVE_{wind} metric gives an instant clue of how their goals are being achieved.
5. When applied to multi-zone, it can provide zone-by-zone evaluation.

Additionally, it can be used for the coarse estimation of the indoor environment during the site evaluation phase, or be integrated with daylight, thermal and energy simulation to support enhanced building simulation. With that, it allows multidisciplinary professionals to communicate more effectively, thus encouraging the engagement of the natural ventilation within the building design process.

Limitations do exist. Its application is restricted to wind-driven natural ventilation, thus neglecting another important natural ventilation driving force, buoyancy. The case study was conducted a limited geometry and the reliability needs to be further investigated. Therefore, the following items are to be conducted as the next step:

- Consider the buoyancy effect and implement $NVE_{buoyancy}$ into the system.
- Test with a realistic building design (with multi-zone, realistic occupancy schedule, and cooling loads).
- Validate the results.
- Get feedback from real users, and find practical issues and errors.
- Link to the state-of-the-art technology and expand the simulation capability: link to CFD or FFD program, or analytical models.

It is an encouraging fact that more CFD interfaces are being introduced to communicate with building geometry within a 3D modeling platform. Such interfaces are *Butterfly*(beta) and *RhinoCFD*. *Butterfly*, a family group of *Ladybug* and *Honeybee*, is a plug-in tool that enables to run CFD in *Rhinoceros*. Its engine is *OpenFoam*. *RhinoCFD* by CHAM is another CFD plug-in tool for *Rhinoceros*. The ability of these tools to run CFD within a 3D modeling platform may open an opportunity to strengthen the parametric system proposed in this paper. For example, they can assist in obtaining more reliable C_p values by running an external airflow simulation with the same geometry created for parametrization, thus reducing

errors that would have been caused by interpolating geometries created in different software.

Acknowledgement

This research is supported by the Harvard Office of Sustainability. Authors would also like to thank Salmaan Craig, a researcher at the Harvard Center for Green Buildings and Cities, for his valuable feedback and discussion.

Nomenclature

A : area of window (m^2)

ACH : air change rate per hour

ACH_{avail} : air change rate per hour available under given climate and design

ACH_{req} : air change rate per hour required to remove q

c : specific heat of air ($kJ/kg-^{\circ}C$)

C_d : discharge coefficient of window

C_p : pressure coefficients of wind at windows

$C_{p,lowrise}$: pressure coefficients of low-rise buildings calculated by Swami and Chandra (1988)

$C_{p,highrise}$: pressure coefficients of high-rise buildings calculated by Swami and Chandra (1988)

G : natural log of S , $G = Ln(S)$

H : height from the ground (m)

H_{met} : height at which meteorological data are measured

NVE_{wind} : ratio of ACH_{avail} to ACH_{req}

\dot{q} : heat rate (kW , kJ/s)

Q : airflow rate (m^3/s)

Q_{avail} : airflow rate available under given climate and design (m^3/s)

Q_{req} : airflow rate required to remove q (m^3/s)

S : ratio of the width of the wall under consideration to the width of the adjacent wall

$T_{comfort}$: target air temperature ($^{\circ}C$)

T_{in} : indoor temperature ($^{\circ}C$)

T_{out} : outdoor temperature ($^{\circ}C$)

v : wind velocity (m^2/s)

v_H : wind velocity at H (m^2/s)

v_{met} : wind velocity at H_{met} (m^2/s)

V : volume of room (m^3)

XL : ratio of the horizontal distance of the point from the edge of the wall to the length of the wall

$Xr = (XL - 0.5)/0.5$.

ZH : the ratio of the distance of the point from the ground to the height of the wall

a : exponent determined by the characteristic of a terrain

a_{met} : exponent of the terrain where meteorological data are measured

δ : layer thickness determined by the characteristic of a terrain

δ_{met} : layer thickness of the terrain where meteorological data are measured

ρ : air density (kg/m^3)

θ : angle between wind direction and outward normal of the wall under consideration (rad)

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