# Evaluating natural ventilation cooling potentials during early building designs

Jun Cheng[1], Dahai Qi[1], Ali Katal[1], and Liangzhu (Leon) Wang[*2]

*1 Centre for Zero Energy Building Studies, Department of Building, Civil and Environmental Engineering, Concordia University, 1455 de Maisonneuve Blvd. West, Montreal, Quebec, H3G 1M8, Canada*

*2 Centre for Zero Energy Building Studies, Department of Building, Civil and Environmental Engineering, Concordia University, 1455 de Maisonneuve Blvd. West, Montreal, Quebec, H3G 1M8, Canada*
**Corresponding author: leon.wang@concordia.ca, lzwang@gmail.com*

## ABSTRACT

Natural ventilation (NV) is an efficient way of cooling buildings, and its energy saving potentials however depend on many parameters including local hourly weather and climate conditions, types of ventilations, indoor cooling loads (or heat gains), operating schedules, window types, and opening-wall ratios etc. Determination of the NV flow rate is thus challenging, although there are many empirical equations for different NV strategies, e.g. single-sided and cross-ventilation, considering different driving forces, e.g. wind, buoyancy and a mix of both. The main objectives of this study are to select coefficients for naturally ventilated buildings with a typical shape based on the existing empirical formulas, use the selected coefficients to develop a quick and relatively accurate method of evaluating NV potential for energy-saving analysis during early building design stages. By utilizing computational fluid dynamics (CFD), a series of computational simulations were conducted to calculate ventilation flow rate with different ventilation variables such as the wind incidence angle and the height of the building. Using the method developed, GIS maps for NV potentials of North America were created in a similar way as the well-known solar potential maps. These maps provide key graphical information of energy saving potentials of NV in terms of total hours, and associated energy savings suitable for NV for over 50 cities in the US and 10 cities in Canada.

## KEYWORDS
Natural ventilation potentials, building energy savings, GIS maps, evaluation,

## 1 INTRODUCTION

Driven by pressure difference due to wind and/or stack effects across building envelopes, natural ventilation (NV) is an effective and natural way of cooling building and reducing building energy usage while improving indoor air quality (when outdoor air is fresher than indoors). Therefore, it has been widely applied in the buildings.

According to opening locations, there exist two main types of NV: single-sided ventilation and cross-ventilation. In single-sided ventilation, only one façade is designed to have openings. In contrast, cross-ventilation has two or more openings on adjacent or opposite façades. The prediction of NV is challenging since it is closely related to the wind aerodynamics regime and the building's location, orientation, shape, window-to-wall ratio etc. Therefore, the decision whether to apply NV or not often needs to be made during early stages of building design, e.g. at the conceptual design stage, which is based on the analysis of the NV energy-saving potential. Since many details of the building are unknown at this stage and an in-depth engineering analytics (e.g. detailed whole-building computer simulations) is thus impossible and also unnecessary considering the time and cost, such an early analysis demands a quick and relatively accurate method to determine NV airflow rates and compare different ventilation strategies based on a relatively simple strategy, such as a set of empirical equations.

Previous studies show quite a few empirical equations regarding airflow rate estimation for both single-sided ventilation and cross-ventilation under wind driven NV (Allard and Santamouris, 1998; Cockroft and Robertson, 1976; Crommelin and Vrins, 1988; H. Wang and Chen, 2012; Warren and Parkins, 1985). Although each of the empirical equations may apply to its specific case, they have more than one unknown parameters or coefficients that have not been identified for typical building shapes and types. As a result, it is hard to apply them to generic buildings for the early NV designs. Therefore, it is necessary to develop a simple and accurate method which can be directly used for the selection of coefficients for typical and generic buildings during the early design stage.

The objectives of this study are to select coefficients for naturally ventilated buildings with a common and typical shape based on the existing empirical formulas, using the selected coefficients to develop a quick and relatively accurate method of evaluating NV potential for energy-saving analysis during early building design stages. A series of CFD simulations were conducted to determine ventilation flow rate with different ventilation variables such as the wind incidence angle and the height of the building, which are compared with wind tunnel data. Using the method developed, GIS maps for NV potentials of North America were created following a similar way as the well-known solar potential maps.

# 2 METHODOLOGY

## 2.1 Empirical formulas

Based on our communications with NV consulting firms, a typical modern NV building may be assumed to be flat-roofed, symmetrical, less than six floors and the effect of internal partitions is neglected. Equations (1) and (2) were selected from the previous studies (Allard & Santamouris, 1998; Cockroft & Robertson, 1976), to calculate wind-driven single-sided ventilation and cross-ventilation flow rates, respectively. The selected equations are simple and applicable due to less unknown parameters compared to other equations available in the literature. For purposes of generalization, only the wind-driven NV is considered at this stage of the study, as the effective use of the force of buoyancy depends more greatly on the building's interior layout.

Single-sided ventilation:

$$Q = \frac{dv}{dt} = \pm \frac{1}{2} f C_D A \sqrt{\left| U_r^2 - \left(\frac{2\gamma P_a}{\rho V}\right) v \right|} \quad (1)$$

Cross ventilation:

$$Q = \sqrt{\frac{Cp_1 - Cp_2}{\frac{1}{A_1^2 C_{D_1}^2} + \frac{1}{A_2^2 C_{D_2}^2}}} U_r = \sqrt{\frac{\Delta C_p}{\frac{1}{A_1^2 C_{D_1}^2} + \frac{1}{A_2^2 C_{D_2}^2}}} U_r \quad (2)$$

where $dv$ is the decrease in volume of the original mass of air inside the building ($m^3$), $V$ is total volume of the building ($m^3$), $t$ is the time (s), $\gamma$ is the specific heat ratio of air which equals to 1.4 for adiabatic flows and 1.0 for isothermal flows (Haghighat, Brohus, & Rao, 2000), $\rho$ is the density of air ($kg/m^3$) and $P_a$ is the atmospheric pressure (Pa). Besides the opening area $A$ ($m^2$) and reference wind velocity $U_r$ (m/s), there are two key undetermined coefficients $f$ and $\Delta C_p$ for the evaluation of airflow rates under single-sided and cross ventilation respectively. According to Anderson et al. (Andersen, Heiselberg, & Aggerholm, 2002) and Wang et al. (L.

Wang, Pan, & Huang, 2012), other critical coefficients related to airflow rates, such as wind velocity coefficients $K$ and $\alpha$ for wind profile correction and discharge coefficients $C_D$ for window type selection, are simplified as constants.

The airflow rates through the openings under different scenarios, e.g. different wind incidence angles, can be determined by CFD simulations. Then the two key coefficients $f$ and $\Delta C_p$ can be calculated by Eqs. (1) and (2). $f$ and $\Delta C_p$ are correlated as the function of wind direction, and have little relation with the number of floors for low-rise residential buildings. The CFD simulation model is introduced in section 2.4.

For a given cooling load defined by the internal total cooling load (or heat gain), $Q_{in}$, the resultant indoor air temperature $T_i$ could be obtained by:

$$T_i = \frac{Q_{in}}{mC} + T_o \quad (3)$$

where $m$ is the mass flow rate of air from the NV, $C$ is the specific heat of air and $T_o$ is the outdoor air temperature.

The annual NV potential is quantified by the total number of hours in a year when the resultant indoor air temperature $T_i$ falls within the defined acceptable comfort range for the occupants of the building. Section 2.2 list the evaluation approach using the empirical equations.

## 2.2 Evaluation approach

The methodology for the development of coefficient selection guidance and evaluation method is summarized as the procedure *a~f*:

a. Choose building location, window facing, and weather data. Determine $f$ and $\Delta C_p$.
b. Choose type of terrain: open area, sub-urban, or urban, and determine $K$ and $\alpha$.
c. Choose the type of the window: casement, tilt, sliding window, and the value of $C_D$ could be determined.
d. Enter other parameters, such as building size, window area etc.
e. Calculate airflow rates, $T_i$, by Eq. (3).
f. Count annual NV hours based on the thermal comfort temperature range and calculated $T_i$. Then calculate energy savings can be determined.

## 2.3 GIS maps

To guide the NV early design, a NV potential map was created using geographic information system (GIS), which is a system designed to capture, store, manipulate, analyze, manage, and present spatial or geographic data. GIS maps have been widely applied for solar potential application (Šúri, Huld, & Dunlop, 2005; Šúri, Huld, Dunlop, & Ossenbrink, 2007). Follow the approach described in section 2.2, NV hours and for buildings in different locations were calculated. In this study, annual NV applicable hours of the North America were calculated, which provide key graphical information of energy saving potentials of NV buildings in terms of total hours suitable for NV for over 50 cities in the US and 10 cities in Canada. The weather condition data use TMY weather files.

### 2.4 CFD simulation

To calculate the airflow rate, a CFD model was developed. The building is 80 m × 25 m × 14.4 m (L × W × H) and is placed within a larger computational domain which has an upstream length of 4W, a lateral length of 4L on both sides and a vertical length of 4H above the building height as Jiang et al. (Jiang, Alexander, Jenkins, Arthur, & Chen, 2003), except instead of 8W, there is a slightly shorter downstream length of 6W in this study to reduce computational time. The building has four floors and uniformly distributed thirty-two windows on each long side (depends on ventilation strategy). With the consideration of the balance between energy-saving and daylighting requirements, the window-to-wall ratio (WWR) is set to be 30% in the model. The CFD model was developed in ANSYS 16.2. "CutCell" was selected as the meshing assembly method. Approximately 500,000 meshes were generated with a minimum size of 0.3 m. A steady state Reynolds-Averaged Navier-Stokes (RANS) standard $k - \varepsilon$ turbulence model was selected. To investigate the grid independency, two incidence angles $\theta$ of 45° and 90° with almost three times the number of meshes were used in the same model to compare the airflow rates for both single-sided and cross-ventilation. The results indicate that the difference in airflow rates for the different grid numbers varies from 0.07% to 15%, which is acceptable considering the difference in time consumption between the two scenarios.

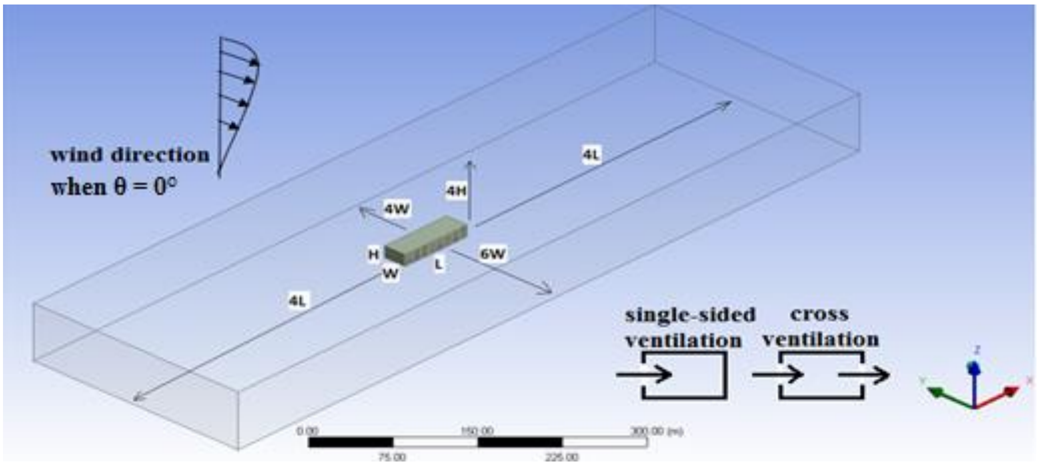


Figure 1: Schematic view of the model with outer domain (W=width, L=length and H=height).

## 3 RESULTS

### 3.1 Validation of CFD modelling method

Reynolds-averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) are the most common turbulence models for the CFD simulations of NV. To determine which model is more efficient and eliminate potential errors, validation study was undertaken using experiments from the literature (Jiang et al., 2003).

Jiang et al. (Jiang et al., 2003) conducted a series of boundary layer wind tunnel experiments in Cardiff University to simulate an urban atmospheric environment by using blockages, fences and Lego Duplo blocks. The model is cubic (250 mm × 250 mm × 250 mm) – see Figure 2. Three cases, including two single-sided ventilation and cross ventilation, were measured. For both windward and leeward single-sided NV cases, there is only one 84 mm × 125 mm opening in one facade. In case of cross ventilation, two openings with the same size are designed in opposite facades. The thickness of the walls was neglected since heat transfer is not considered in this validation study. After acquiring the simulation results, the mean velocity distributions at five locations around and inside model were compared with the Jiang's wind tunnel test results. Both RANS (two-equation standard $k-\varepsilon$ models, precisely) and LES were used and the comparisons are demonstrated in Figure 3:

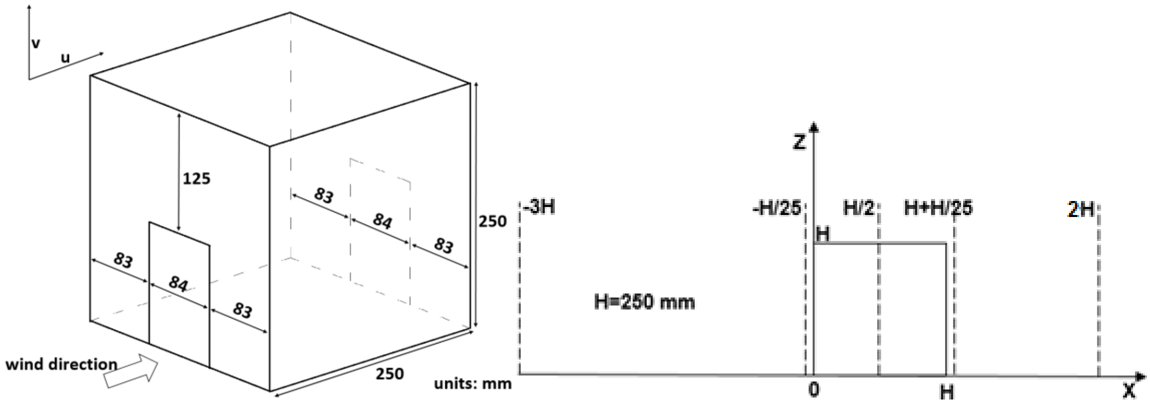


Figure 1: Schematic view of single-opening model and air velocity measurement locations.

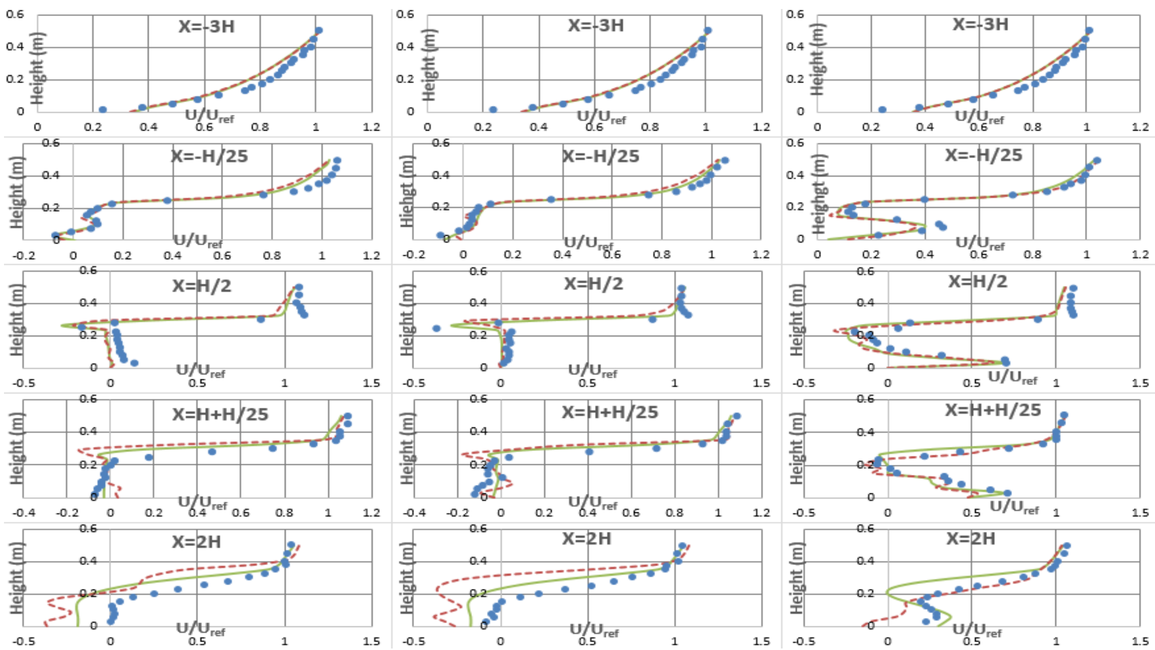


Figure 3: Mean velocity distributions for windward, single-sided ventilation (left column); leeward, single-sided ventilation (middle column) and cross-ventilation (right column). Dots: Experimental values, Jiang et al (Jiang et al., 2003); Solid line: RANS model; Dashed line: LES model.

The overall arrangement between the CFD predictions (RANS and LES) and experimental results is fairly similar along the streamline direction, which is close to the results from Jiang et al. (Jiang et al., 2003). The difference of results between the two models are fairly small at most of the locations. Thus, the RANS standard $k-\varepsilon$ model was selected to conduct the rest of simulations considering it is acceptably accurate and time-efficient comparing to the LES model (Toja-Silva, Peralta, Lopez-Garcia, Navarro, & Cruz, 2015; Tominaga, 2015).

### 3.2 GIS maps for natural ventilation potentials

As an application of this study, the evaluation method based on empirical equations can provide a fast and relatively accurate energy saving potential analysis of NV for engineers and architects during the building early design stage. A typical building is a four-story rectangular building with same dimension as the base model located in open space of Toronto. Specifically, the indoor design temperature range, $T_i$, = 21.5 °C ~ 27.8 °C, is set to achieve 80% thermal comfort acceptability based on the Adaptive Model for naturally ventilated buildings (Brager & De Dear, 2000). This building is set to be an office building with a combined internal heat gain of 70 W/m$^2$ (AUTODESK; Chartered Institution of Building Services Engineers (CIBSE), 2015). The figure shown below illustrates the annual NV available hours under both single-sided (SS) and cross NV (CV) scenarios for all different window facing layouts.

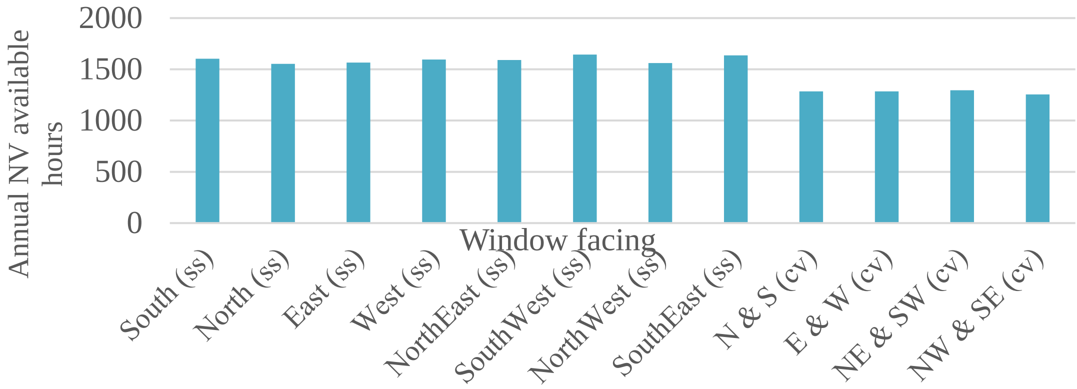


Figure 4: Annual NV available hours in Toronto for an internal cooling load of 70 W/m$^2$.

In detailed calculations, the wind incidence angle $\theta$ for each hour is determined as the angle between hourly meteorological wind direction and the building orientation (i.e. window facing). Then, the value of $f$ and $\Delta C_p$ would be obtained correspondingly for the calculation of hourly airflow rate $Q$ for both ventilation strategies. In combination with the internal heat gain $Q_{in}$, once the indoor air temperature $T_i$ is calculated within the indoor design temperature range, that hour would be counted as an NV applicable hour. Specifically, for the case in Fig. 4, the building in Toronto achieves the maximum energy saving potential of 1,644 hours with the southeast facing single-sided NV.

Repeat the previous steps for the southeast facing single-sided NV buildings in the other major cities in US and Canada, we are able to plot the annual NV applicable hours using the GIS map visualizations in Figs. 5 and 6. It indicates that the maximum NV hours could be more than 2,500 hours and 80,000 kW in the US and 1,600 hours and 50,000 kW in Canada. The numbers could be used to determine the energy saving potentials of using NV and identify the optimum initial building designs for achieving energy savings during the conceptual design stage.

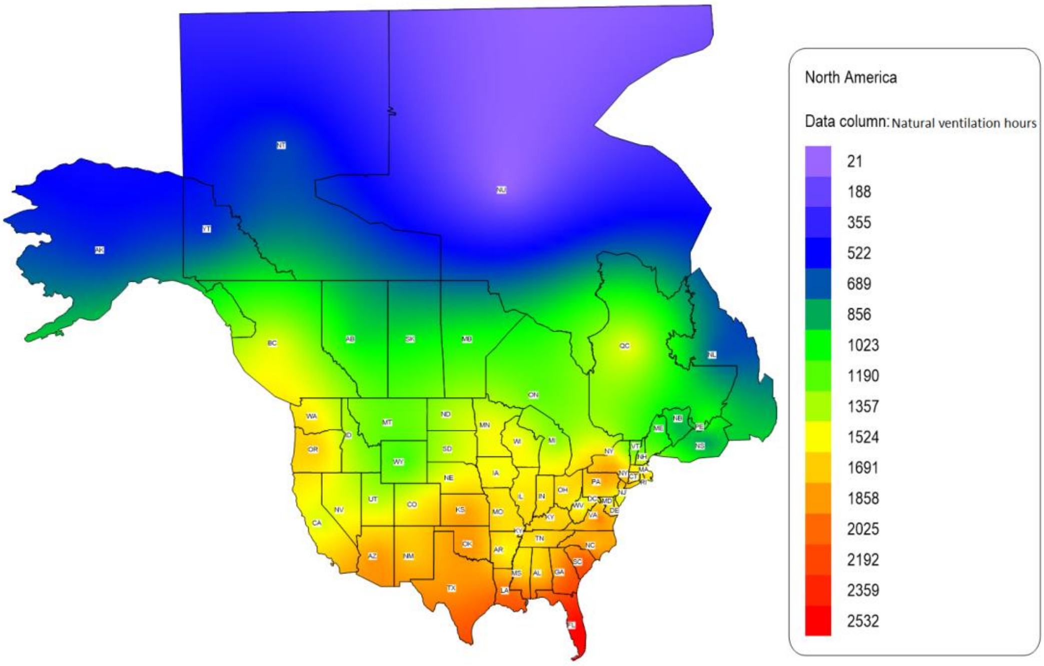


Figure 5: GIS map of NV potential hours (single-sided, building orientation: southeast) for the cooling load of 70 W/m$^2$.

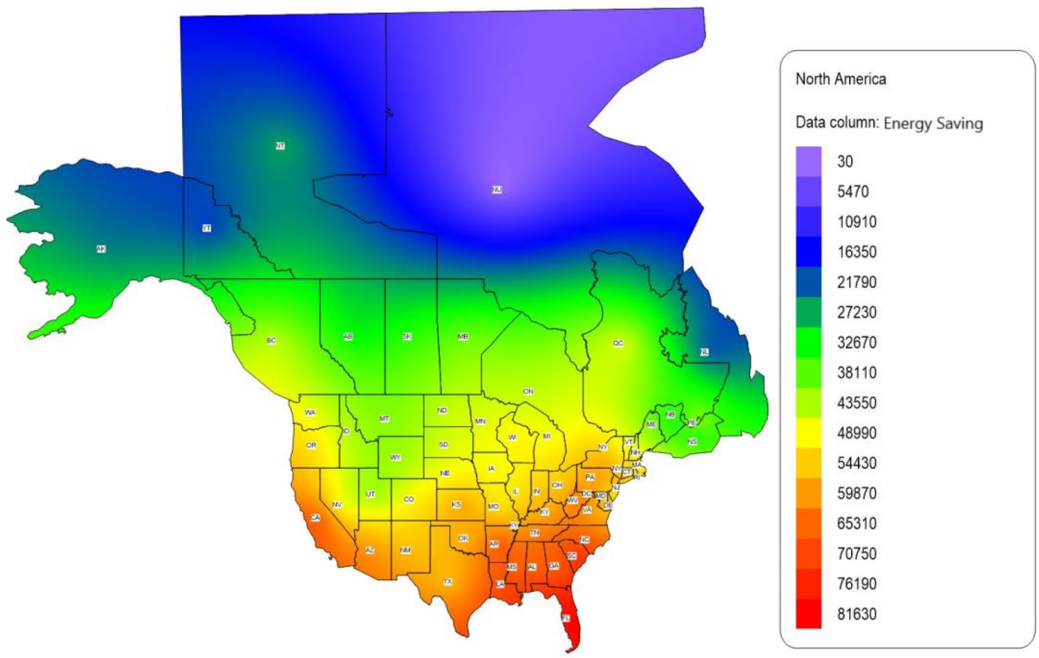


Figure 6: GIS map of NV potential energy savings, kW (single-sided, building orientation: southeast) for the cooling load of 70 W/m$^2$.

## 4 CONCLUSIONS

Natural ventilation has been widely used in buildings as an efficient way of reducing building energy usages and improving indoor air quality. However, determination of the NV energy saving potential is challenging because the naturally-driven airflow rates depend on many parameters including local hourly weather and climate conditions, types of NVs, amount of heat gains, operating schedules, window types, and opening areas percentages etc. This study aims to select coefficients for naturally ventilated buildings with a common shape based on the existing empirical formulas, and use the selected coefficients to develop a quick and relatively accurate method of evaluating NV potential for energy-saving analysis during early building design stages. Using the method developed, GIS maps for NV potentials of the North America were created in a similar way as the well-known solar potential maps. The maps provide key graphical information of energy saving potentials of NV in terms of total annual NV applicable hours and energy savings for over 50 cities in the US and 10 cities in Canada. It was found that for the building defined in this paper, the maximum NV hours could be more than 2,500 hours and 80,000 kW in the US and 1,600 hours and 50,000 kW in Canada for single-sided ventilation with southeast building orientation. The proposed method and the GIS maps can be used to determine the viability of using NV and make initial building design decisions for energy savings during the conceptual design stage.

## 5 REFERENCES


Allard, F., & Santamouris, M. (1998). Natural ventilation in buildings: a design handbook. In *London James James* (p. 378).

Andersen, K. , Heiselberg, P., & Aggerholm, S. (2002). Naturlig ventilation i erhvervsbygninger (in Danish). *Statens Byggeforskningsinstitut*.

AUTODESK. Example Internal Loads for Different Space Types. https://doi.org/https://sustainabilityworkshop.autodesk.com/buildings/equipment-and-lighting-loads

Brager, G. S., & De Dear, R. (2000). A standard for natural ventilation. *ASHRAE Journal*, *42*(10), 21–28. https://doi.org/10.1017/CBO9781107415324.004

Chartered Institution of Building Services Engineers (CIBSE). (2015). *Guide A: Environmental design* (8th ed.). Norwich: Page Bros. (Norwich) Ltd.

Cockroft, J. P., & Robertson, P. (1976). Ventilation of an enclosure through a single opening. *Building and Environment*, *11*(1), 29–35. https://doi.org/10.1016/0360-1323(76)90016-0

Crommelin, R. D., & Vrins, E. M. H. (1988). Ventilation through a single opening in a scale model. *Air Infiltration Review*, *9*(3), 11–15.

Haghighat, F., Brohus, H., & Rao, J. (2000). Modelling air infiltration due to wind fluctuations—a review. *Building and Environment*, *35*(5), 377–385. https://doi.org/10.1016/S0360-1323(99)00028-1

Jiang, Y., Alexander, D., Jenkins, H., Arthur, R., & Chen, Q. (2003). Natural ventilation in buildings: Measurement in a wind tunnel and numerical simulation with large-eddy simulation. *Journal of Wind Engineering and Industrial Aerodynamics*, *91*(3), 331–353. https://doi.org/10.1016/S0167-6105(02)00380-X

Šúri, M., Huld, T. A., & Dunlop, E. D. (2005). PV-GIS: a web-based solar radiation database for the calculation of PV potential in Europe. *International Journal of Sustainable Energy*, *24*(2), 55–67. https://doi.org/10.1080/14786450512331329556

Šúri, M., Huld, T. A., Dunlop, E. D., & Ossenbrink, H. A. (2007). Potential of solar electricity generation in the European Union member states and candidate countries. *Solar Energy*, *81*(10), 1295–1305. https://doi.org/10.1016/j.solener.2006.12.007

Toja-Silva, F., Peralta, C., Lopez-Garcia, O., Navarro, J., & Cruz, I. (2015). Roof region dependent wind potential assessment with different RANS turbulence models. *Jnl. of Wind Engineering and Industrial Aerodynamics*, *142*, 258–271. https://doi.org/10.1016/j.jweia.2015.04.012

Tominaga, Y. (2015). Flow around a high-rise building using steady and unsteady RANS CFD: Effect of large-scale fluctuations on the velocity statistics. *Journal of Wind Engineering and Industrial Aerodynamics*, *142*, 93–103. https://doi.org/10.1016/j.jweia.2015.03.013

Wang, H., & Chen, Q. (2012). A new empirical model for predicting single-sided, wind-driven natural ventilation in buildings. *Energy and Buildings*, *54*, 386–394. https://doi.org/10.1016/j.enbuild.2012.07.028

Wang, L., Pan, Y., & Huang, Z. (2012). Factors Affecting Discharge Coefficient of Building Ventilation Windows (in Chinese). *Building Energy Efficiency*, *40*(6).

Warren, P. R., & Parkins, L. M. (1985). Single-sided ventilation through open windows. In *Conf. proc. Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE, Florida* (Vol. 49, p. 20).