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Simulation of Natural Ventilation in the Early Design of Near Zero Energy Buildings

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Abstract

Various parameters affect the performance of natural ventilation of buildings. The most time-consuming parameter to estimate prior to a performance simulation of natural ventilation for a certain building geometry is wind pressure coefficients on the building façade. This time consumption is critical in the early stages of the building design process where building geometry (and consequently the wind pressure coefficients) may change rapidly. This paper therefore presents an analysis of the effect of building geometry on wind pressure coefficients and, consequently, the building performance. The results indicated that overall building geometry and neighbor surroundings have a significant impact on the wind pressure coefficient whereas façade roughness has low impact. Building designers can therefore use the same wind pressure coefficients to evaluate several façade proposals in the early design stage – as long as the overall building geometry and neighbor surroundings are kept constant. This realization will save time in the design process and enables designers to focus on developing parameters most sensitive to performance when evaluating and adjusting design proposals.

Keywords – Natural Ventilation; Integrated Energy Design; Building Performance Simulation; Near Zero Energy Building

1. Introduction

The European Performance Building Directive states that all new buildings constructed after 2020 should consume "near zero energy" [1]. This demand requires that design decisions in the early design phase are based on careful considerations about their potential impact on energy efficiency. A potential strategy in the design of near zero energy buildings is to decrease the use of mechanical fan power. This can be accomplished by proper use of natural or hybrid ventilation.

Calculating the performance of natural ventilation requires inputs regarding wind pressure, buoyancy force and pressure drop through openings. All these inputs are highly affected by the building geometry which is constantly changing in the early design phase. However, evaluating the effect of a building design on the performance of natural ventilation using building simulation is currently a process that most likely will interfere with the need for rapid performance assessments in the early design stage. There is thus a need for building simulations tools with rapid yet precise algorithms for simulation of natural ventilation performance. Such algorithms already do exist, e.g. the one described in [2]. In these algorithms (and also more sophisticated ones), it is especially the estimation of the wind pressure coefficients of a specific building geometry that are difficult and time-consuming. It might be possible to determine the coefficients using data from the rather large body of research on how building shapes affect the wind pressure coefficient, e.g. [2-9], but not all building geometries imaginable are (with good reason) represented. Another more generic approach is to select the necessary accuracy on wind pressure coefficients (C_p) by investigating how the magnitude of C_p-values affects the performance of a design proposal. This paper therefore presents a sensitivity analysis of C_p-values on the annual building performance. The aim of the analysis is to enable building designers to make fast estimates of appropriate C_p-values in the early design stages. The analysis encompasses some typical geometrical design parameters.

2. Method

A sensitivity analysis on annual performance of indoor climate and energy efficiency was carried out to test which geometrical parameter to consider when estimating C_p-values for input to an annual building simulation. First, several variations of C_p-values were estimated for several building geometries (see section 2.2). These C_p-values were used as input to an hourly calculation of natural ventilation rates (described in section 2.1), and these rates were then used in a building simulation tool to simulate the annual performance. All simulations were made in the same reference room (described in section 2.3) only changing the C_p-values. Finally, the annual performances of the room with different C_p-values were compared in several combinations.

2.1. Simplified hourly calculation of natural ventilation rates

The simplified method for estimating natural ventilation rates described in [2] is implemented in an hourly-based thermal simulation tool called iDBuild [10]. The equations of the method are as follows:

$$\Delta P = a \cdot q^2 + b \cdot q \tag{1a}$$

$$\Rightarrow q = \frac{-b+\sqrt{b^2+4a \cdot \Delta P}}{2a} \tag{1b}$$

$$q = C_d A_{eff} \sqrt{\frac{2\Delta P_{window}}{\rho_{inlet}}} \tag{2a}$$

$$\Rightarrow \Delta P_{window} = \frac{\rho_{inlet}}{2 \cdot (C_d \cdot A_{eff})^2} \cdot q^2 = a \cdot q^2 \tag{2b}$$

$$\Rightarrow a = \frac{\rho_{inlet}}{(C_d \cdot A_{eff})^2} = \frac{1.2}{(0.6 \cdot A_{eff})^2} \cdot 10^{-6} \tag{2c}$$

$$\Delta P_{stack} = \rho_{inlet} \cdot g \cdot (H_{outlet} - H_{inlet}) \cdot \frac{T_{in} - T_{out}}{T_{in}} \quad (3)$$

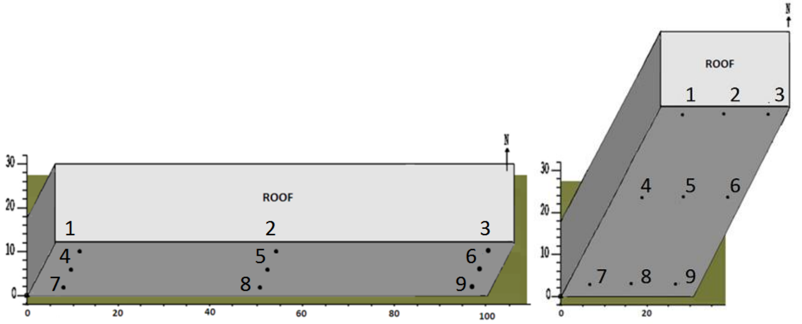
$$\Delta P_{wind} = \left(C_{p.inlet} - C_{p.outlet}\right) \cdot \rho_{inlet} \cdot ½ \cdot v_{met}{}^2 \quad (4)$$

where ΔP_{wind} is the pressure difference between inlet and outlet caused by wind (Pa), ΔP_{stack} is the pressure difference between inlet and outlet caused by buoyancy effect (Pa), ΔP is the addition of ΔP_{wind} and ΔP_{stack} (Pa), q is the air volume rate of natural ventilation (L/s), a is a constant describing pressure drop through the system caused by turbulent flow (Pa s^2/L^2) and is dependent on the window design, b is the constant describing pressure drop through the system caused by laminar flow (Pa s^2/L^2), C_d is the discharge coefficient (set conservatively to 0.6 if unknown) (-), A_{eff} is the effective opening area (m^2), ΔP_{window} is the pressure difference over the window (Pa), ρ_{inlet} is the air density of the incoming air (kg/m^3), g is the gravitational acceleration (m/s^2), H_{outlet} is the elevation level of outlet (m), H_{inlet} is the elevation level of inlet (m), T_{in} is the indoor air temperature (K), T_{out} is the outside/inlet air temperature (K), $C_{p.inlet}$ is the wind pressure coefficient of inlet according to meteorological wind speed (-), $C_{p.outlet}$ is the wind pressure coefficient of outlet according to meteorological wind speed (-), and V_{met} is the meteorological wind speed from weather data (m/s).

In an hourly-based algorithm, ΔP_{stack} is calculated by (3) in every time step using T_{in} from the previous time step and T_{out} in the actual time step. The wind pressure difference between inlet and outlet (ΔP_{wind}) is calculated by (4) in every time step with C_p dependent on the wind direction of the hour and several aspects of the building geometry. The sum of these pressure differences is used in (1b) to estimate the possible amount of natural ventilation rate in the actual time step used for the hourly building simulation. The a-factor is calculated by (2c) dependent on the window opening and the b-factor, if needed, is chosen (e.g. if inlet air is distributed over a perforated extended ceiling). It is the effect of the estimated C_p on annual performance which is subject to the sensitivity study presented in this paper.

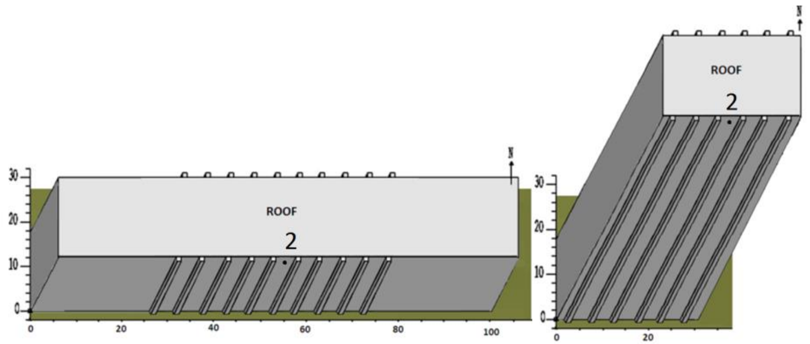
2.2. C_p-values for different building shapes, roughness and surroundings

The C_p-values for all 360 degree of wind directions was calculated on two different building shapes, see figure 1, as well as in the situation of several geometrical changes around these buildings, such as several obstacles along the façade surface (figure 2) and neighbor buildings (figure 3). The dimensions of the two buildings are 30x100m, both with a depth of 18m. Building 1a is shaped as a wide block building, while 1b is rotated to be shaped like a high-rise building. The C_p-values are calculated in CP Generator [11].



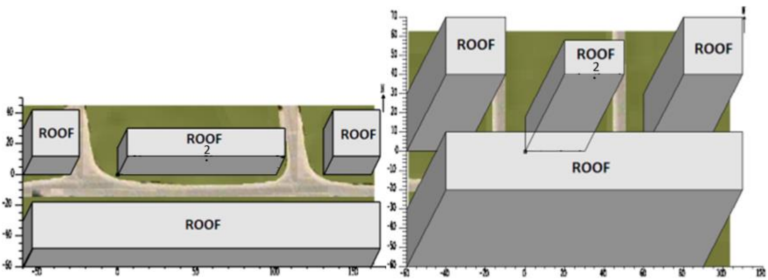
Variation 1a Variation 1b

Fig. 1 Variations of building shape Nine calculation points on each façade.



Variation 2a Variation 2b

Fig. 2 Variations of building shape including a façade roughness of 1 m. One calculation point on each façade, respectively to point 2 on 1a and 1b.



Variation 3a Variation 3b

Fig. 3 Variations of building shape including neighboring buildings. One calculation points on each façade, respectively to point 2 on 1a and 1b.

Comparing the nine calculations point marked on 1a and 1b (fig 1) with each other on each façade will show the sensitivity of using the precise inlet location or not. Comparing the nine calculation point on 1a with the respectively nine points on 1b will show the sensitivity of differences in building shape. Difference between 1a and 2a as well as between 1b and 2b will show the sensitivity of differences in façade "roughness" (e.g. obstacles along the façade surface). Comparing the nine calculation point of 1a and 1b to the respectively nine points on 3a and 3b will show the sensitivity of neighboring surroundings.

The difference between the calculated C_p-values of inlet and outlet are shown in figures 4-9 together with the simplified C_p from [2] for all 360 degree of wind directions indicated by an angle of target. The more sophisticated C_p-values calculated in CP Generator has generally lower ΔC_p-value than the simplified ΔC_p-values from [2] especially in the situation with neighbor buildings (Figure 8-9). Hypothetically this mean that the use of simplified values from [2] will simulate better annual performance than use of more sophisticated C_p-values which increase the risk of designing a building with poor natural ventilation. The ΔC_p-values are generally higher in 1b than 1a which indicates that the wind pressure around a high rise building is larger than around a less tall block building (figure 4-5). The location on the façade of an inlet has an effect on the ΔC_p-values, especially for vertical location on a high rise (figure 5). Changes in ΔC_p-values caused by neighbor buildings are relatively larger compared to scenarios without neighbor buildings as the neighbor building will shelter from some wind directions and increase the pressure from other directions. Changes in ΔC_p-values caused by obstacles on the façade surface (a roughness on the façade) are small, however noticeable.

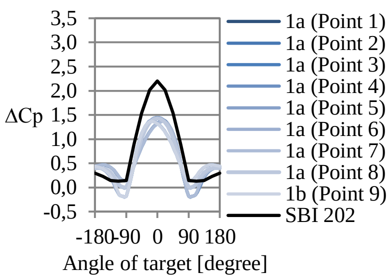


Fig. 4 Cp-difference between inlet and outlet (located on roof) of nine calculation point in 1a comparrd to values from SBI 202 for an exposed wall in a flat country site.

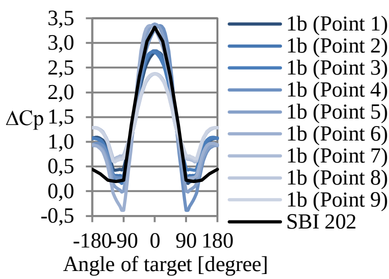


Fig. 5 Cp-difference between inlet and outlet (located on roof) of nine calculation point in 1b comparrd to values from SBI 202 for an exposed wall in a flat country site.

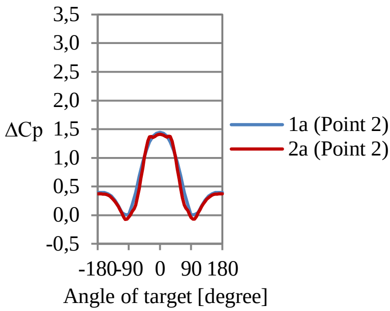


Fig. 6 Cp-difference between inlet and outlet (located on roof) of calculation point 2 in 2a compared with point 2 in 1a.

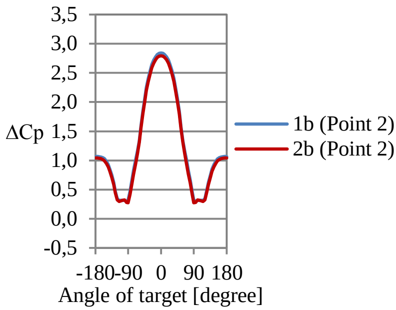


Fig. 7 Cp-difference between inlet and outlet (located on roof) of calculation point 2 in 2b compared with point 2 in 1b.

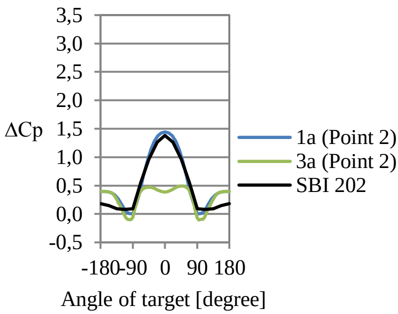


Fig. 8 Cp-difference between inlet and outlet (located on roof) of 3a compared with 1a and with values from SBI 202 for an exposed wall in a city center area.

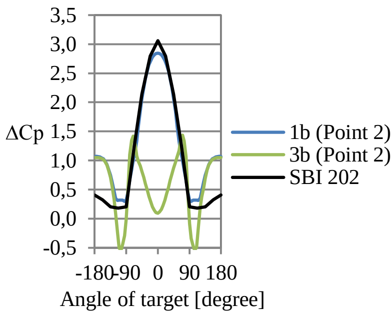


Fig. 9 Cp-difference between inlet and outlet (located on roof) of 3b compared with 1b and with values from SBI 202 for an exposed wall in a city center area.

2.3. Reference room for simulations

A reference room of a landscaped office room fulfilling indoor class II according to EN 15251 [12] is used for performance simulations in the sensitivity analysis. Four people are located in the room each working with a computer of 50 W. Their clothing are adaptive to the season. The dimensions of the room are shown in figure 10. A ventilation gab located near the ceiling for natural ventilation was designed as a 300 mm ribbon window without glazing and able to tilt up to 5 degrees and with an initial discharge coefficient of 0.6. The outlet opening is practically located at the same high as the inlet to eliminate the buoyancy effect and by that increase the sensitivity of wind pressure conditions. The heat capacity the room is categorized as middle heavy, the façade wall (the only surface facing outside) is insulated by 300 mm mineral wool and the windows has three-layer glass (U=0.76, g=0.40, LT=0.53). Heating set points was 20 °C, and the building automation was able to increase ventilation rate up to 6 h^{-1} when operative temperature was >24 °C. Outside the occupant time the set points were 15 °C and 24 °C, respectively. Minimum ventilation rate was set to fulfill the indoor air quality class II [12], and infiltration was set to 0.14 h^{-1}. In the occupied time, the general lighting was controlled continuously after a horizontal illuminance level of 200 lx at desk level in the middle of the room, and the task light was controlled on/off for 500 lx according to the Danish lighting standard [13]. Light was diming continuously with daylight level from 8 W/m^2 (200 lux) to 0.5 W/m^2. Task light was 1 W/m^2.

The sensitivity analysis was carried out in the tool iDbuild [10] which is able to conduct integrated hourly thermal and daylight level calculations. The weather data used for the simulations was the Danish design reference year.

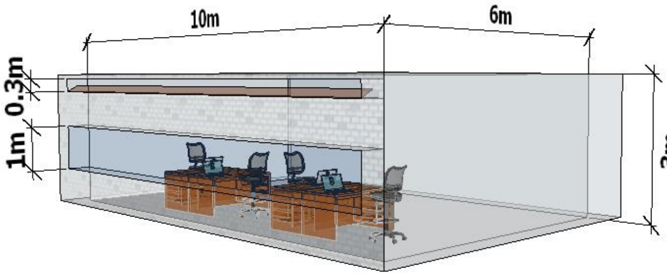


Fig. 10 Internal dimensions of reference office room used for sensitivity analyse.

3. Results

In all simulations of the sensitivity analysis, the sensitivity on air quality was significant whereas sensitivity on thermal climate and energy need was limited. This paper therefore presents only the sensitivity on air quality (fig. 11-13).

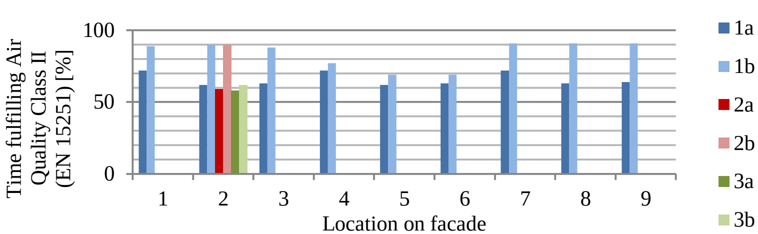


Fig. 11 Air quality of north oriented office room.

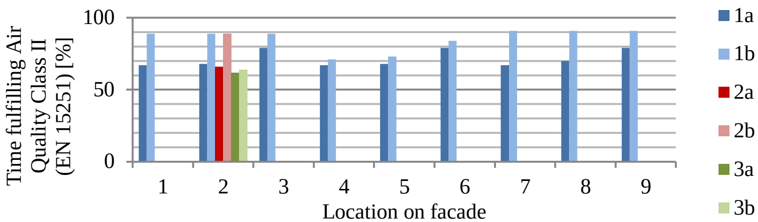


Fig. 12 Air quality of south oriented office room.

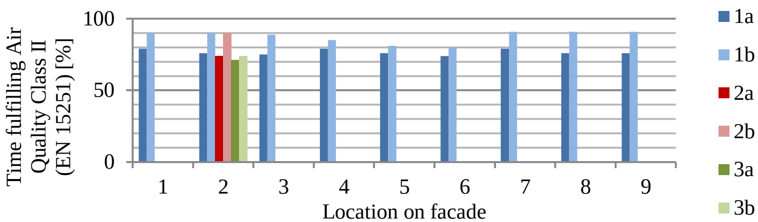


Fig. 13 Air quality of west oriented office room.

Comparing annual performance on air quality of the different variations, the consequence by not considering several design parameters is shown in table 1. The results indicate that it is relatively important to consider the building shape and the neighbor surroundings since these design parameters are affecting the annual performance of air quality with up to 45%. If the locations are close to each other, as vertically in a block building or horizontal for a high rise building, the difference by using C_p-value from neighbor inlet locations is only up to 13 %. For instance, it would be reliable only to consider a representative room of a whole floor section in a high rise building. Using C_p-values of an unsmooth surface compared with a smooth surface changes the air quality by less than 5 % which indicates that the complexity of calculating C_p-values of an unsmooth façade surface (which might change constantly in an early design process) is not worth considering when designing. Furthermore, using too simplified C_p-values from [2] causes up to 35 % change in annual results.

Table 1. Summary of C_p sensitivity between different variations described as % of occupied hours with poor air quality (i.e. not fulfilling category II EN 15251 [12]).

		Difference in % of occupied time NOT fulfilling air quality class II			
		Absolute[1]		Relative[2]	
		Min	Max	Min	Max
Using too simplified C_p-values (SBI 202[2] vs. Cp Generator)		-18	19	-25	35
Not considering the primary shape of a building (1a vs. 1b)		-11	28	6	45
Not considering specific inlet location in C_p (Point 5 vs. rest of points)	On 1a	-11	2	-14	3
	On 1b	-22	2	-24	3
Not considering specific inlet location in C_p vertical (Point 3-5 vs. rest of points)	On 1a	-2	0	-3	0
	On 1b	-22	-1	-24	-6
Not considering specific inlet location in C_p horizontal (Point 2,5,8 vs. rest of points)	On 1a	-10	3	-14	4
	On 1b	-11	2	-13	3
Not considering neighbor buildings in C_p	1a vs.3a	4	6	7	10
	1b vs.3b	26	38	22	45
Not considering façade structure of 1m roughness in Cp (1a vs. 2a + 1b vs. 2b)		0	3	0	5

[1] "*Absolute*" indicates the difference between two performance results in % of occupied time.
[2]"*Relative*" indicates the difference between two performance results divided by one of the performance results. This indicates the relative change in a performance result by not considering a certain geometry parameter.

4. Conclusion

The result of the sensitivity analysis indicates that some design parameters are more important than others to consider when calculating wind pressure coefficients for annual building simulation. For instance, the primary shape of the building and neighbor surroundings may cause up to 45% change in the annual performance in terms of air quality whereas the smoothness of the façade only impact the annual performance by maximum 5 %. Furthermore, it has been found that if the building is big, the façade should be divided into subareas before simulations since a distance of approximately 30 m between two inlet areas on a building may cause a difference in performance of up to 24 %.

In building design practice, the neighbor surroundings are usually well-defined from the beginning of the project. Furthermore, building designers tend to decide on the primary building shape before defining the façade geometry. This analysis indicated that designers can use the same C_p-values to evaluate several façade proposals – as long as the overall building geometry and neighbor surroundings are kept constant. This realization will save time in the design process and enables designers to focus on developing parameters most sensitive to performance when evaluating and adjusting design proposals.

It is important to notice that the sensitivity analysis only applies for the Danish climate and the method for estimating natural ventilation used in this analysis gives an estimation of the maximum ventilation rate in hourly time steps. There is lot of uncertainties in this estimation since the wind is very transient and dynamic in reality: weather conditions might change every second instead of only every hour as in the simulation. Wind gusts will affect the performance of natural ventilation and may cause paper to be blown down of tables or make human feel uncomfortable draft. Designers must therefore also consider indoor air flow patterns caused by natural ventilation before making design decisions.

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