UNCERTAINTIES IN AIRFLOW NETWORK MODELLING TO SUPPORT NATURAL VENTILATION EARLY STAGE DESIGN

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ABSTRACT

Despite a lot of Integrated Design Process guidelines and procedures have been developed in the last few years, more specific energy design procedures are needed to push the implementation of passive design techniques.
As natural ventilation design influences strongly the building shape and aspect, it has to be considered since the early design stages and its effect should be correctly predicted and proved by means of suitable tools and methods. In this respect, airflownetwork models seems a promising modelling techniques as they are already integrated in the existing dynamic building simulation tools and they have a quick solver. On the other hand, the simplicity of these models implies uncertainties in a lot of input parameters, first of all the wind conditions. The urban wind environment is a stochastic phenomenon, and as consequence the ventilation performance in a naturally ventilated building changes. An accurate wind analysis should be supported by weather data collected on site and by an external CFD simulation at urban scale. Discharge coefficients and external convection coefficients could be accurately estimated by laboratory tests. This would mean additional design costs (and time) and need of expertise in the field. A key issue of this work is to assess the thermal-airflow model reliability in airflow prediction when accurate estimation of input data is not feasible.
This paper presents an uncertatinty analysis performed on a dynamic simulation model of a new office building naturally ventilated during the night.
Full-factorial parametric analysis have been performed to assess the influence of the input parameters on the model reliability. Possible input ranges have been estimated and organized in a tree-structure to investigate the effect of dependent parameters like wind velocity profile, wind pressure coefficients, discharge coefficients, and external convection coefficients.
Significant variations in air change rates are shown that reflect an uncertainty of +/- 2% on total cooling loads in respect to the base case simulation result. No direct correlations between outdoor environmental conditions and air change rates have been found as the discharge coefficients affect significantly the results.
The design proposal supported by quantitative analysis and results prediction uncertainty assessment can be taken into consideration more seriously by the design team. The obtained results can be generally extended to airflownetworks with similar airflow paths.

KEYWORDS
Airflow network, uncertainty analysis

INTRODUCTION

Since 1993 a lot of Integrated Design Process guidelines and procedures have been developed [1]. They are mainly focused on team work methods, design evaluation and design strategy and, to the knowledge of the authors, no pragmatic energy design procedures have been yet developed to push the implementation of passive design techniques (among which natural ventilation strategies) and to model their effectiveness.
As natural ventilation design influences strongly the building shape and architectural impact, it has to be considered since the early design stages and its effect should be correctly

predicted and proved by means of suitable tools and methods. To face this issue, airflownetwork models seems a promising modelling techniques as they are already integrated in the existing dynamic building simulation tools and they have a quick solver.

However, the model implies assumptions on pressure distribution on the building and its interaction with the internal airflows, that cannot be accurately assessed unless additional design costs (and time), that need expertise and possibly laboratory facilities, are invested. A key issue of this work is to assess the thermal-airflow model reliability in airflow prediction when accurate estimation of input data is not feasible.

The paper presents an uncertatinty analysis performed on a model of a new office building naturally ventilated during the night, simulated with a dynamic Energyplus. The obtained results can be generalized for further airflownetwork models.

BUILDING MODEL

Building description

The case study of the present work is one of the new office buildings placed in the new Technology Park in Bolzano (Italy). The building is architecturally conceived as a black monolithic block with a nearly-square plant. It has five above ground floors and an underground floor. The main entrance is on the north side of the ground floor and on the south side there is the expo area. The upper floors will host offices, meeting and service rooms, whereas in the underground floor there will be several conference rooms. In the centre of the building and through the full height, a green patio is designed as a buffer zone to improve indoor comfort and daylighting.

The envelope is a metal-glass façade with a solar shading system in the south façade and a black surface with different strips of horizontal windows in the other facades. The horizontal windows on north, east and west façade are positioned on the inner side of the external wall. In this way, the deep reveal due to the wall thickness and the low height of the windows work as a sun shading system and the glazed part of the façade will not be visible from the outside perspective.

Natural ventilation strategies

A night stack driven cross ventilation was chosen as the most effective configuration that balances performances needs with constrains given by fire compartments, acoustic comfort and privacy needs in the offices during the working hours. [2]

To increase the height difference between inlet and outlet openings, connecting floor vents will be applied. This solution fulfils the architect’s requests by reducing the movable part in the façade and by keeping free the internal layout of the spaces. Inlet and outlet openings are automatically controlled top hung windows. The floor vents are closed during the working hours to avoid acoustic discomfort and maintain privacy between offices.

The foyer is directly connected to a lightwell and to the hall of every floor and is ventilated through a stack driven cross ventilation to avoid overheating situations.

Due to safety reasons underground floor and expo areas are mechanically ventilated. A small office area in the center part of the building is single-sided ventilated and connected with the green patio.

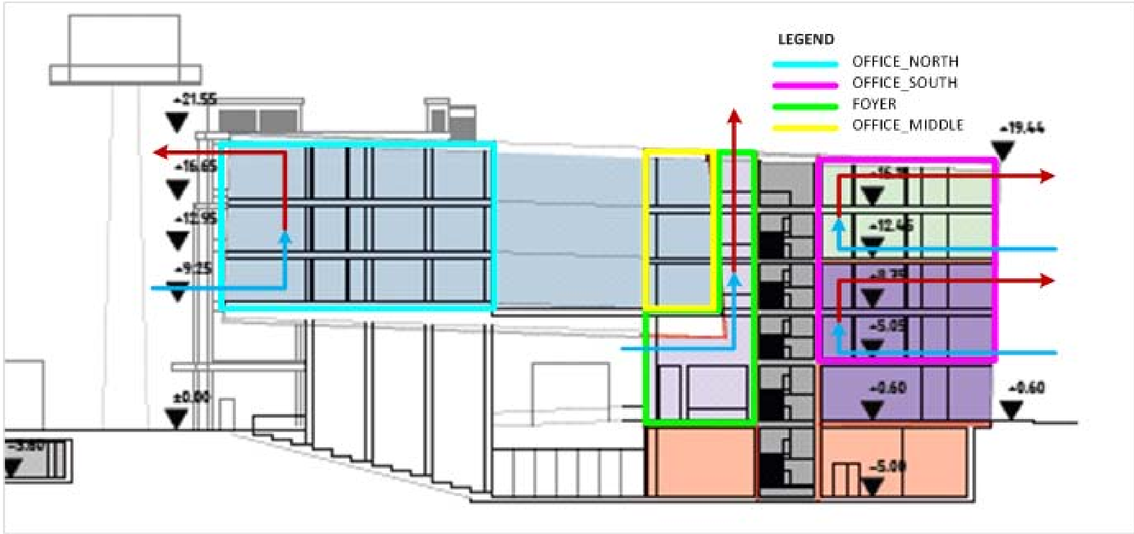

Figure 1. Cross section of the building fire regulation plan with fire compartments, model zones and a scheme of the selected stack-driven cross ventilation configurations for the considered zones.

Energyplus modeling to study airflows

The original Energyplus building model zoning has been re-thought to introduce an airflownetwork. Particular care has been taken to reduce computational time as the uncertainty analysis requires to perform parametric analysis running several simulation.

The building has been divided into thermal zones with the same temperature and pressures, occupation patterns, internal gains, major exposure, cooling setpoints. Thermal zones have been further on divided depending on the planned airflow paths and linkages. Building airflow zoning can be more detailed than building thermal zoning as Energyplus airflownetwork allows only one temperature node per thermal zone.

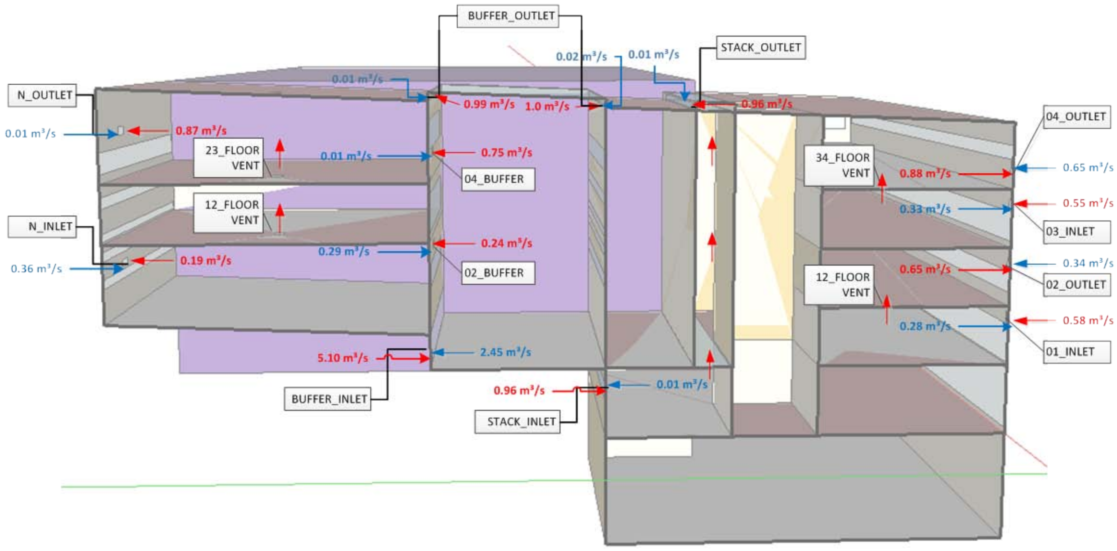

Figure 2. Section of the Energyplus geometry model in sketchup with average airflowrates during summer season. Red and blue arrows represent respectively positive and negative airflow directions.

According to fire compartments and natural ventilation strategies, three airflownetworks are set: a first network involves the office block on the south side of the building, the second network involves the atria zones and the stack and a third network involves the office block on the north side of the building.

It is important to detail the window area and the height from the ground level (Table 1). Horizontal window series and floor vents series have been modeled using multiplier as they have the same size and the same height from the ground level. In this way window shape effects are taken into account properly and less input objects are necessary to set window controls.

Zone group	Airflownetwork component name	Opening type	Height [m]	Area [m²]	Nr of windows	Tot. opening area [m²]
OFFICE_ SOUTH	01_INLET	Top hung window	7.5	0.65	16	10.40
	02_OUTLET	Top hung window	10.9	0.65	18	11.70
	03_INLET	Top hung window	14.6	0.54	26	14.04
	04_OUTLET	Top hung window	16.8	0.80	26	20.80
	12_FLOOR VENT	Horizontal opening	8.2	1.60	9	14.40
	34_FLOOR VENT	Horizontal opening	15.6	1.60	10	16.00
OFFICE_ NORTH	N_INLET	Top hung window	10.6	0.54	10	5.37
	N_OUTLET	Top hung window	19.0	0.74	10	7.39
	04_BUFFER	Top hung window	17.6	0.71	4	2.85
	02_BUFFER	Top hung window	11.7	0.71	4	2.85
	N23_FLOOR VENT	Horizontal opening	12.4	0.60	9	5.40
	N34_FLOOR VENT	Horizontal opening	16.1	0.60	9	5.40
BUFFER ZONE	BUFFER_INLET	Top hung window	21.5			8.00
	BUFFER_OUTLET	Top hung window	21.5			8.00
STACK	STACK_INLET	Top hung window	3.4	-	-	8.70
	STACK_OUTLET	Top hung window	22.0	-	-	8.70

Table 1. Airflownetwork surface components area and height from the ground.

An opening factor of 0.5 has been set for top hung window assuming a maximum opening angle of 45°.

This may cause inaccurate shadowing and daylight distribution inside the building, but the computation time decreases. However, daylight study is not one of the purposes of this work and opening area is only a small percentage of the whole glass area. For the same reason a full exterior solar distribution with no reflections has been set. Reflections would have required also no-convex zones, that would have meant setting more zones. [3]

Energy Managment System objects are used to introduce simple controls on windows and vents opening [4]. Indoor and outdoor temperature variables have been set as sensors and venting opening factors as actuators. A program was written to activate natural night ventilation between 8 pm and 8 am if the following conditions are fulfilled :

– indoor temperature is higher than 24°C;
– indoor temperature is higher than outdoor dry bulb temperature;
– outdoor dry bulb temperature is higher than 10°C.

External nodes at every floor height and with different orientations have been set to take into account more accurately wind pressure conditions and model stack effects.

Floor vent interzone surfaces references an horizontal opening component with a 90° sloping pane angle. Horizontally pivoted detailed openings are used to model inlet and outlet top hung windows.

An ideal loads air system template, with cooling setpoint temperature of 26°C during working hours, has been implemented to evaluate cooling loads without taking into account the plant system. Infiltration rates have been neglected, as the building tightness required by the local standard is restrictive and will be proven by blowerdoor test.

Simulations have been run from June to September. Average airflownetwork volume flow rates are shown in Figure 2. Simulation results of the base case model have showed that the airflow direction do not always follow the positive direction of the airflow path: it works in the 86% of activation hours on the upper floors and in the 46% of activation hours in the lower floors. This could be due to the lower opening area in the 1st and 2nd floor. The graph in Figure 3 show the airflow frequencies through the inlet-outlet components in the south office block airflownetwork. It could be noticed that low airflow rates are more frequent in the negative airflow direction.

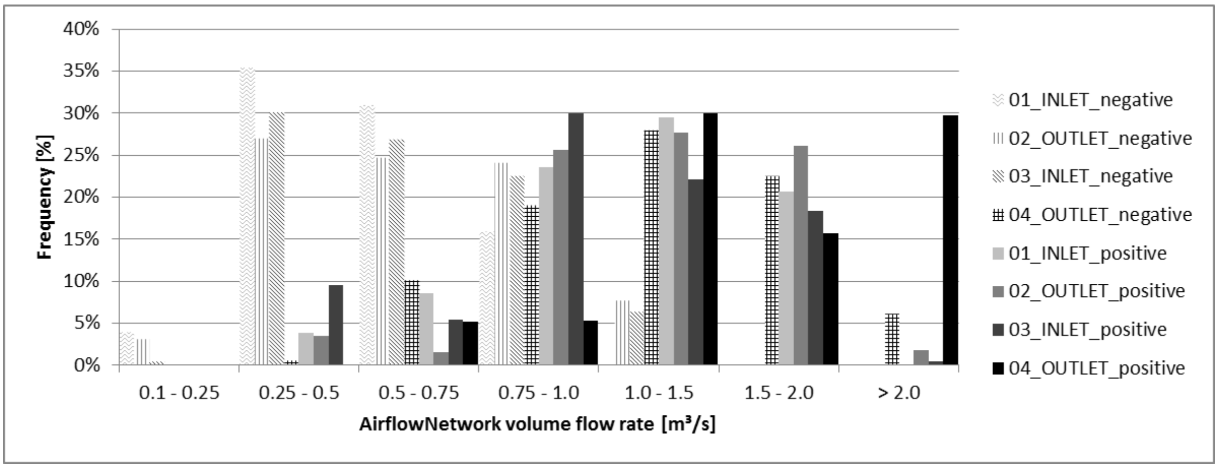

Figure 3. Natural volume flow rate frequency along the airflownetwork paths in the south office block.

MAIN UNCERTAINTY SOURCES ON AIRFLOW PREDICTION

Apart uncertainties derived from model assumptions and approximations, the main uncertainty sources in airflow prediction can be ascribed to the input data:

- Leakage's geometry, position and flow characteristics (discharge coefficient)
- External and internal temperatures
- Wind pressures

Opening position determines buoyancy pressures and external wind pressures. Discharge coefficients are considered in the airflow network models as a fixed property of an opening, which depends on its shape and Reynolds number. However, when an opening is installed in an envelope, the actual discharge coefficient may differ from the fixed one. Etheridge D. (2012) [3] provides some boundaries that can be placed on the uncertainties.

Whereas external temperatures are supposed to have low uncertainty, internal temperatures are affected by uncertainties due to the heat transfer - airflow model coupling. Hensen J.L.M. et al. (1995) [6] stated that coupling problems can be overridden by setting a proper time step. Therefore temperature uncertainties are affected mainly by convection coefficients. The external convection coefficients depend on inside-outside temperature difference, wind speed and direction and surface roughness. The internal convection coefficients depend on inside-outside temperature difference, zone airflow regime, surface orientation and heat flow direction. Furthermore vertical temperature profiles (stratification) cannot be reproduced by a multizone airflow model, as the temperature distribution is considered uniform in every zone.

The stochastic features of the urban wind environment affect the naturally ventilated building performances. An accurate wind analysis should be supported by weather data collected on site and by an external CFD simulation at urban scale, to assess wind pressure coefficients on the building envelope.

Parametric studies have been performed on Energyplus Airflow Network model by means of jEPlus program [7] to analyse the sensitivity of the model to different combination of dependent and independent parameters. Possible input ranges have been estimated and organized in a tree-structure (Figure 4) to investigate the effect of these input parameters on airflow rate prediction.

The presented parametric analysis aims at assessing the model uncertainty by:

1) assigning a range and a discrete distribution for each input parameter;
2) executing the model in full-factorial design mode[1];
3) assessing the airflow rates prediction variation rates and its effect on cooling need calculation.

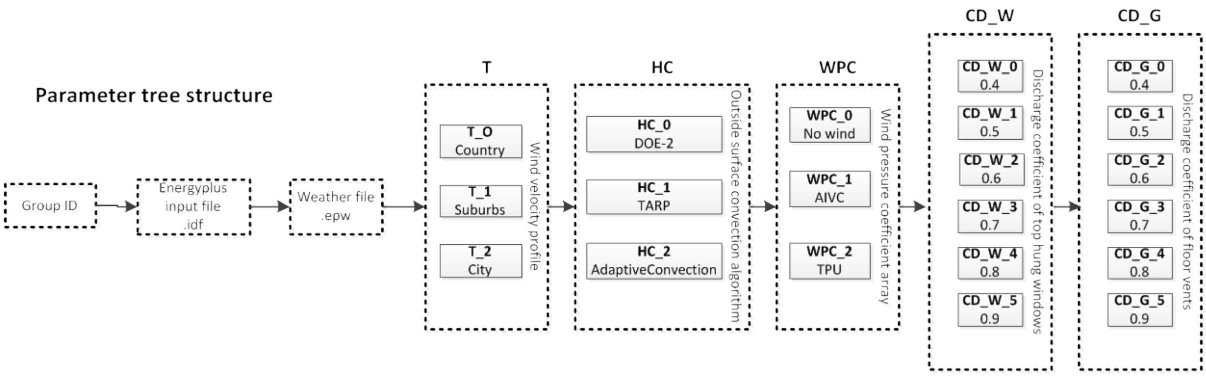

Figure 4. Parameter tree structure set in jEPlus. Each simulation job is a path from the root node of the tree to a leaf of the tree, with each node containing an optional value of the corresponding parameter. As a result, the total number of jobs encoded in the tree corrisponds to the total number of paths from the root to the leaves.

Wind velocity profiles

EnergyPlus converts wind velocity weather data through numerical method that considers the differences between the weather station location and the building site, according to:

$$U_{\infty} = V_{met}\left(\frac{\delta_{met}}{z_{met}}\right)^{a_{met}}\left(\frac{z}{\delta}\right)^{a} \qquad (2)$$

where z is the height from the ground, z_{met} is the height of the standard metereological wind speed measurement, and a and δ are terrain-dependent coefficients that determine the wind velocity profile.

Terrain type field in the building object associates different values of wind speed profile exponent and height. Three different wind velocity profiles (Table 2) have been taken into account in the parametric analysis.

Terrain type	Exponent, α	Boundary layer thickness, δ (m)
Country	0.14	270
Suburbs	0.22	370
City	0.33	460

Table 2. Wind speed profile coefficients. Source: energyplus engineering reference

Outside surface convection algorithm

Energyplus users can select which model equations or values to apply for the exterior convection coefficients calculation. There are five models based on ASHRAE correlations and different flat plate measurements: SimpleCombined, TARP, MoWitt, DOE-2 and AdaptiveConvectionAlgorithm.

Simple combined model returns higher values as also radiation to sky, ground and air is included in the exterior convection coefficient, whereas all other algorithms yield a purely

[1] A full factorial experiment is an experiment whose design consists of two or more factors, each with discrete possible values, and whose experimental units take on all possible combinations of these levels across all such factors.

convective heat transfer coefficient. MoWitt model can be applied only to very smooth vertical surfaces. DOE-2 model is a combination of MoWitt and BLAST. TARP model is very similar to BLAST and detailed convection models. The adaptive convection algorithm assigns default equations to surfaces depending on their outside face classification, heat flow direction and wind direction.
The graph in Figure 5 compares the exterior convection coefficients for a vertical surface calculated by TARP and DOE-2 model depending on wind speed, façade position respect to wind direction and different surface roughness. A fix temperature range has been assumed. DOE-2 model is more affected by wind speed than the TARP one.

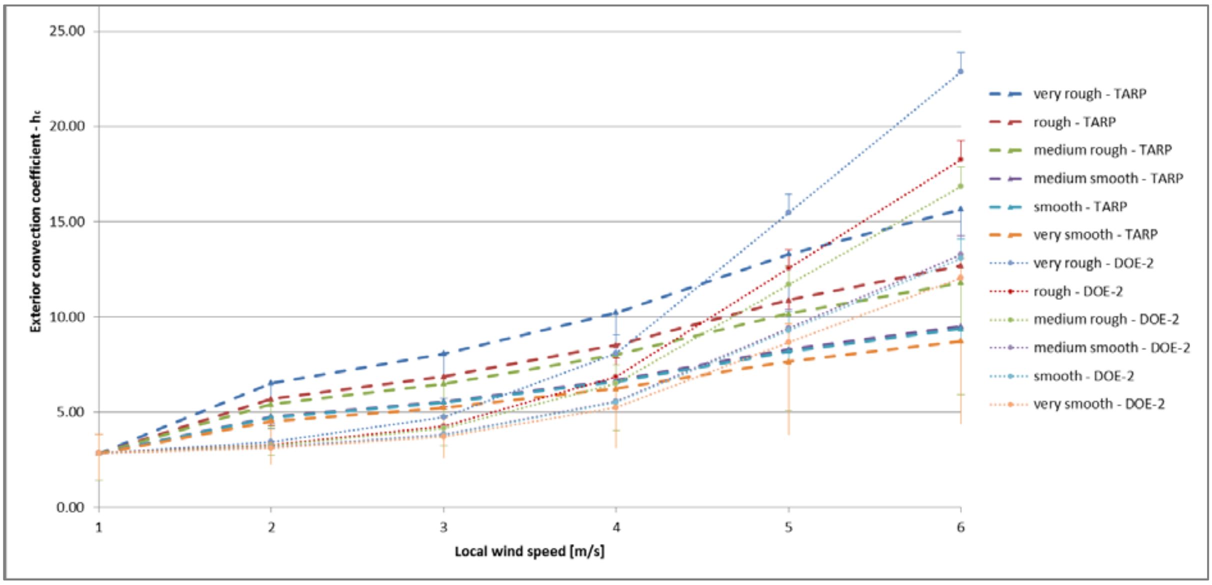

Figure 5. Vertical wall exterior convection model comparison depending on wind speed and surface roughness at a fixed temperature difference.

Wind pressure coefficients

Wind pressure coefficients are used to calculate wind-induced pressures on each façade surface during simulations and are defined as the ratio of static pressure to dynamic pressure at a given point on the façade:

$$c_p = \frac{P_x - P_0}{P_d} \tag{1}$$

where P_x is the static pressure at a given point on the building façade (Pa), P_0 is the static reference pressure (Pa), P_d is the dynamic pressure (Pa).
They can be evaluated in detail according to different approaches:

- full-scale measurements
- reduced-scale experiments in wind tunnels
- computational fluid dynamics (CFD) simulations

However these approaches are not suitable to early stage design simulations as they are time-consuming and requires additional costs. Therefore, analytical models and database are most often used in building energy simulation and airflownetwork tools [8].
For the present case study, surface-averaged c_p have been avoided as more openings per façade are present and the magnitude of their uncertainty is high [9].
C_p coefficient used in the parametric analysis are extracted from two main existing database.
The Air Ventilation and Infiltration centre (AIVC) database [10] is based on the interpolation of data from published material. Wind pressure coefficient datasets are available for low rise buildings with different exposion conditions and with different length to width ratio. The coefficient sets used for the analysis are extracted from the low rise building database with length to width ratio of 1:1 and surrounded by obstructions equal to the height of the building.

The Tokyo Polytechnic University (TPU) aerodynamic database [11] is a web based database on wind tunnel experiments on 12 test cases including low and high rise buildings with varied eaves. The coefficient sets used for the analysis are extracted from the low rise building database with flat roof, height to width ratio of 1:4 and length to width ratio of 2:2.
A wind pressure coefficient array of null values has been introduced in the parametric analysis to evaluate the influence of wind pressures on output results.

Discharge coefficients
The discharge coefficient is required as input in airflow models and is defined by Equation 1.

$$c_d = \frac{q}{A}\sqrt{\frac{\rho}{2\Delta p}} \qquad (2)$$

where q is the volume flow rate across the opening (m^3/s), A is a defined open area (m^2), ρ is the air density (kg/m^3) and Δp is the airflow difference across the opening (Pa).
Airflow predictions are linearly dependent on discharge coefficients and therefore they imply directly proportional results uncertainty.
The Equation 1 is applied to openings installed in a surface separating two much larger spaces in still-air conditions, with uniform and equal densities. In practice flows through openings are generated by wind and buoyancy forces. The wind modifies the external flow field, whereas the buoyancy forces cause different air densities. As Etheridge D. (2012) stated [4], the installation effects are negligible for air vents and small windows in case of low velocity ratio and for large stacks in case of inward flow only. In particular, this effect depends primarily on the magnitude of V/u_m (typical values range from 1.5 to 9), where V is the cross flow velocity and u_m is the spatial mean velocity through the opening.
As much as opening angles is smaller the uncertainty is higher, because leakages along all other sides of the opening account for a relative large part of the opening area.
It is to underline that these effects are dependent on wind velocity and direction. Therefore the parametric analysis has to be applied simultaneusly to discharge coefficients, wind velocity profile and wind pressure coefficient sets on the façade.
Johnson et al. (2012) compared airflow network predictions with measured airflow values and found that the discrepancy in the predicted value is due to inaccuracy in the discharge coefficient, which was an estimated value [12].
In the case of buoyancy driven cross ventilation, some measurements were performed on scale model tests [13] but no full-scale model have been yet analysed, especially in the case of horizontal openings.
Two different discrete variables have been set for the floor vents discharge coefficient and for the top hung windows discharge coefficients in the parametric analysis.
Stated Heiselberg's experiments [14], it has been assumed that discharge coefficents have a value bigger than 0.4.

RESULTS
The simulation model has been runned in full-factorial mode for the airflownetwork involving the office block on the south side of the building.
Analyzing the resulting air change rates at fixed outdoor wind and temperature conditions (Figure 6), significant variations with standard deviations up to 0.6 occur.
The lower values in the graph are refered to samples with null wind pressure coefficients. The upper values in the graph are refered to samples with wind pressure coefficients from AIVC database. The smaller variations are due to different discharge coefficient combinations. In presence of wind, discharge coefficient effect is higher than in absence of wind.

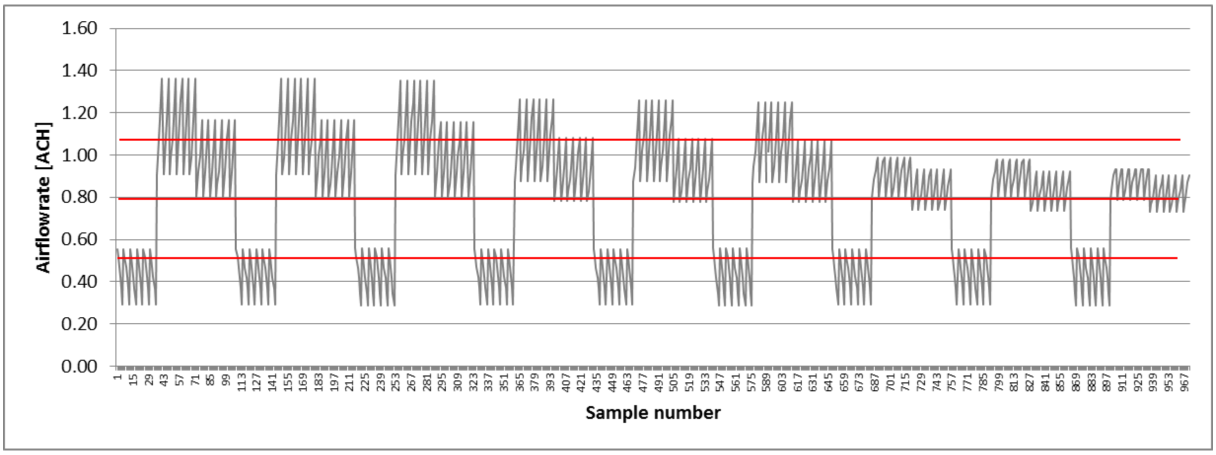

Figure 6. Resulting airflowrates at 22/06 h 21:00 from parametric analysis with 967 samples. Row lines represents average ACH +/- standard deviation.

Figure 7 show the airflow rates calculate for the base case with error bars that represent the variations calculated through the parametric analysis.

Total cooling loads of the office block in the south part of the building have been calculated with the result that the variations in air change rates reflect an uncertainty of +/- 2% on total cooling loads.

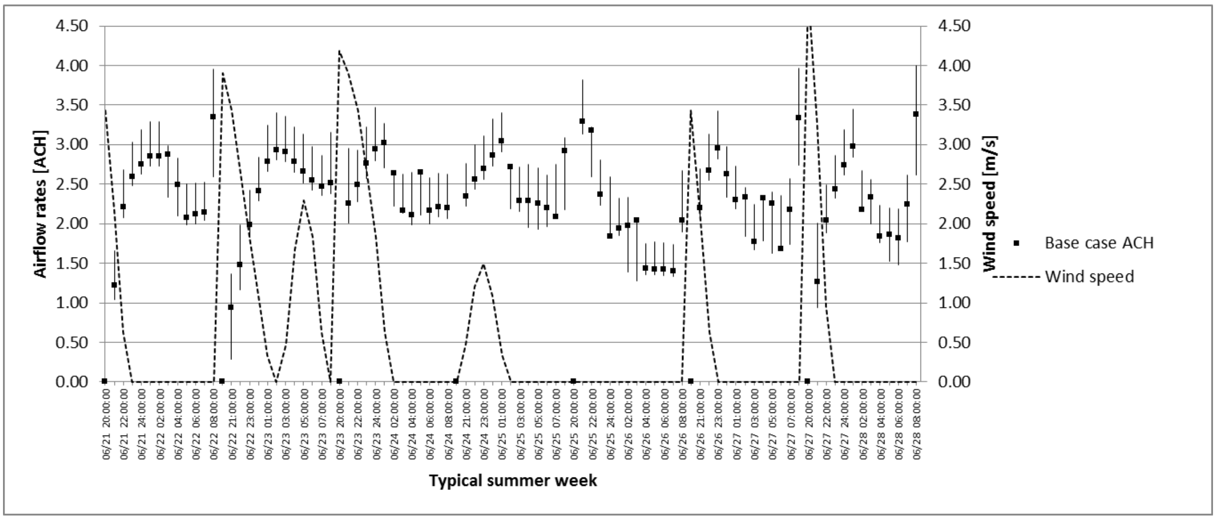

Figure 7. Airflowrates during the typical summer week in the first floor of the building south office part. Points represents the base case results and bars represent the airflow rate possible uncertainties.

Scatter plots in Figure 8 have been performed to find correlation between external environmental conditions and airflowrates. No direct correlation has been found, but it can be noticed that in absence of wind or in case of low outdoor temperatures, the range of standard deviations is larger. This means that, discharge coefficients may affect significantly the results.

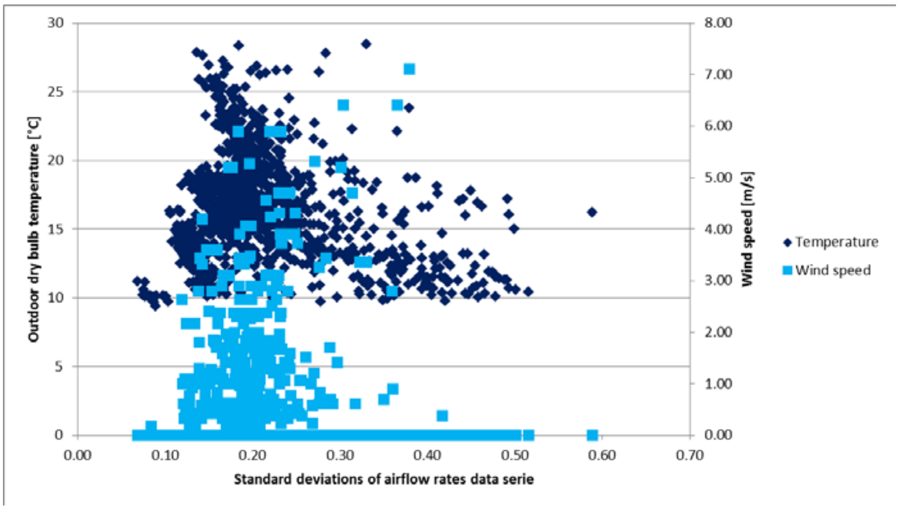

Figure 8. Scatter plot of standard deviations of airflow rate data serie related to wind speed and outdoor dry bulb temperature.

CONCLUSION

These results would be of particular interest for the natural ventilation design support during early design phases and can be generally extended to airflow networks with similar airflow paths.

Significant variations in air change rates are shown that reflect an uncertainty of +/- 2% on total cooling loads.

No direct correlations between outdoor environmental conditions and air change rates have been found as the discharge coefficients affect significantly the results. However, in absence of wind or at low temperatures the standard deviations have a wider range of variability.

Airflow network simulation results are also useful to control the efficacy of the natural ventilation strategy proposed. Simulation results of the base case model have showed that the airflow direction follow the positive direction of the airflow path in the 86% of activation hours on the upper floors and in the 46% of activation hours in the lower floors. Inlet and outlet opening area at 1st and 2nd floor should be increased.

Further developments of the process are planned to optimize opening area and opening controls to prevent natural ventilation strategy disfunctions.

Thanks to this quantitative analysis support, the mentioned natural ventilation strategies can be evaluated in a more rigorous way by the design team, for the building and architectural choices in the early design phases.

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