Urban densification and pressure coefficients of buildings
Evaluating the effect of different building arrangements on Cp values

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ABSTRACT: Pressure coefficients (Cp) are key parameters in wind induced natural ventilation and input data for several thermal performance simulation programs, namely EnergyPlus thru DesignBuilder. However, in both programmes, standard templates for Cp values assume general data that might be inaccurate for the specific urban arrangements evaluated in this research, compromising natural ventilation performance. A CFD numerical algorithm is employed to calculate Cp values on a residential building´s façades. Results indicate the Cp modification in accordance to height above ground and proposed urban densification levels. Space between buildings and surroundings form are significant to change Cp values.
Keywords: pressure coefficients, cfd, urban densification

INTRODUCTION
Despite the availability of several researches about wind pressure coefficients (Cp) [1, 2. 3], simplified parametrical models [4, 5] and algorithms to predict Cp values, the applicability of such data is reduced due to Cp variation, specifically the effect of adjacent buildings in shielded environments such as urban centres.

Usually Cp data are obtained thru wind tunnel technique using solid models. However this technique is not always available due to high costs, time and expertise involved when compared to Computational fluid dynamics, known as CFD. When obtaining Cp values thru wind tunnel technique is not possible, CFD may be applied as a reliable tool to obtain such data [6].

This paper presents a part of a comprehensive research investigating the impacts of urban densification on energy performance of naturally ventilated residential tall buildings. Building´s energetic performance is evaluated using EnergyPlus via its commercial graphical interface (DesignBuilder).

EnergyPlus is one of the main computer programmes to calculate thermal performance of buildings. However, to calculate natural ventilation the programme assumes general data from wind tunnel technique using an isolated building. These standard templates include a series of widely used pressure coefficient for low-rise buildings (up to three stories) and in the case of tall buildings only vertical profile data is provided [1]. Also, for different building geometry, the programme only performs simple corrections on pressure incidence. Nevertheless, the adoption of a vertical profile can lead to misinterpretations of the distribution of pressure coefficients on a surface once it can often omit significant variations which may lead to significant errors in airflow rate calculations [6].

Therefore the use of general Cp data may compromise the analysis of different urban situations evaluated in this research. A set of eight different low to medium urban density scenarios (80 inh/ha to 640 inh/ha) were modelled as clusters of buildings shaped as walls, blocking air flow and playing major role in pressure distribution on the model building´s facades. Alternatively, a commercial CFD numerical algorithm is applied to simulate urban natural wind filed, calculating Cp values at specific points in selected residential units. Later, these data will fill Cp tables in DesignBuilder to properly calculate indoor thermal performance using natural ventilation.

Considering natural ventilation as the main passive strategy for thermal comfort for the city of Fortaleza, in the northeast of Brazil (3°43'S), it is essential to consider it the densification process of the urban fabric that is currently in process in several parts of the city.

URBAN DENSITY SCENARIOS MODELLED
The urban scenarios to evaluate different density possibilities were modelled in CAD and based up on urban legislation for the city of Fortaleza. More specifically, zoning practices adopted correspond to a part of town indicated as a Preferred Occupation Zone (Z.O.P.), where higher urban density is allowed and even encouraged.

The geometry of all scenarios is simplified due to computational capacity resources available and to reproduce different urban arrangements. In the preparation of each one of the eight models, nine typical urban blocks (100 m x 100m) were distributed in a 3 x 3 array. In the central block, four model buildings representing the maximum occupation allowed (72 m height) and also considering some of the aspects of local real estate market.

Within the other eight blocks the occupation varied according to urban requirements such as retreats, occupancy rate and building height. The purpose is to test different urban forms and density levels (expressed as inhabitants per hectare) to evaluate the permeability of the flows and their impact on Cp values at six points at windward façade and six points at leeward façade of a model building (Figure 1). These set of points correspond to the centre of windows on the first floor and the twenty-third floor.

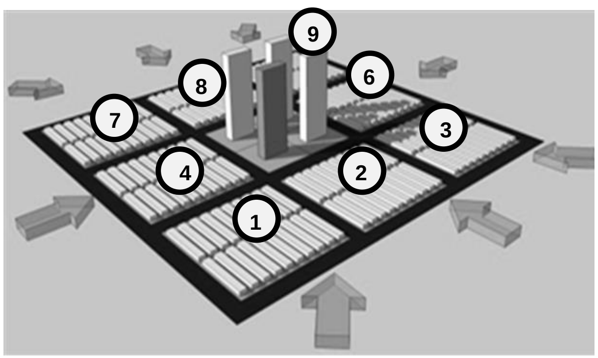

Figure 1: Urban cluster base for modelling the eight different density scenarios

The sizing of the domain used for simulations should avoid the blocking effect in which the walls or physical boundaries may influence the flow. Thus, a distance of fifteen times the largest dimension of the biggest obstacle was considered to determine the size for leeward regions and properly capture vortices effects.

WIND DATA ANALYSIS

For a proper use of natural ventilation as a strategy for passive cooling of buildings, frequency and intensity of the local wind should be consider. Thus, local wind data collected by city´s airport were organized to determine main the occurrence of wind speeds and directions. Data analysed is the period between February 12, 2002 and December 29, 2011, a total of 86,544 hours.

Within this range, 76,595 hours were consider as valid records (89% of the total hours) and thus analysed using WRPLOT View 6.5.1. The wind rose plotted determined two predominant wind directions: east and southeast directions with 44% and 34% of total hours, respectively, followed by the south direction, accounting for 16%. Then, average wind speed for each direction in 45° increments was calculated and became input data for the set of CFD simulations.

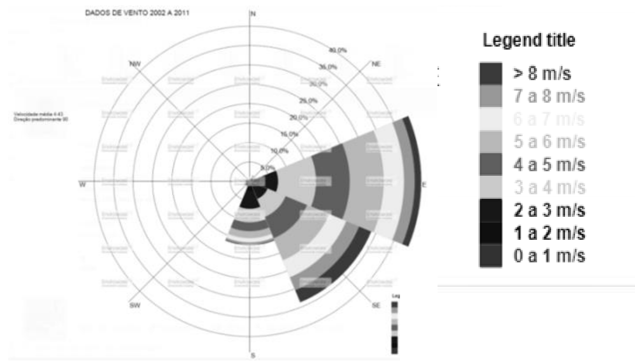

Figure 2: Wind rose for the city of Fortaleza 2002 – 2011.

THE SIMULATIONS PERFORMED

Currently a wide range CFD tools is available and they're progressively being applied to simulations involving fluids in motion. Computational fluid dynamics programs are based on Navier-Stokes equations that are solved at all points of a two or three dimensional mesh. The mesh represents the buildings and surrounding areas. In these models, pressure and velocity are given for determining initial and boundary conditions [7].

In the present research ANSYS CFX 14.0 is used to simulate wind field thru the urban environment and density clusters, calculating Cp values at the facades of a model building. A Core i-7 processor with 8gb RAM was used to calculate a set of 64 simulations (8 wind incidence angles for 8 different scenarios).

An octagonal domain was designed in order to analyse the main wind directions. Within this domain, unstructured and finer resolution meshes with tetrahedral elements were prepared. This specific mesh generation mode is faster and easily adapts to geometry details such as model building´s characteristics. Also prism layers were added to the domain´s ground and surfaces of buildings to capture boundary layer effects.

CFD simulations performed were considered isothermal, steady-state and turbulent. Domain´s ground and buildings surfaces were considered smooth surfaces. The sides of the domain are defined as openings and the top is considering free slip.

Standard K – ε turbulence model is used. This turbulence model remains in common use despite advances in computer power and the use of other turbulence models such as large eddy simulation (LES) [8]. The choice for this particular turbulence model is due to its robustness and once attempts on the use of RNG K – ε and SST models didn´t reach suitable results in a set of several preliminary tests performed.

Three points were inserted at windward façade (points 1, 2 and 3) while other three points were inserted at the leeward façade (A.S. 1, A. S. 2 and WC) at each of the two analysed floors.

Table 1: urban density level and total mesh elements for each of the eight scenarios analysed

Scenario	(Urban Density)	(Mesh elements)
SCENARIO 001	160 inh/ha	5.041.089
SCENARIO 002	320 inh/ha	4.138.487
SCENARIO 003	80 inh/ha	8.624.348
SCENARIO 004	160 inh/ha	8.581.203
SCENARIO 005	40 inh/ha	6.863.710
SCENARIO 006	320 inh/ha	2.899.153
SCENARIO 007	480 inh/ha	4.804.441
SCENARIO 008	640 inh/ha	4.700.880

Simulations were programmed to end as a final solution when a residual of 1 x 10^{-4} could be reached or after 500 interactions. In addiction monitor points were inserted to check pressure at buildings façades. In every set of simulations these values stabilized after a few iterations, attesting the precision of the solution.

RESULTS

Despite the simulation of all wind directions in 45° increments, the results discussion specifically assesses the main wind incidences evidenced by the local wind diagnosis, which indicated the predominance of east, southeast and south wind incidences. Other wind directions results, which amounted only 6% of total hours, will be analysed at another time.

Firstly, for east wind direction, Cp values varied as expected in most of the scenarios evaluated. Perpendicular incidence on main façade allows direct ratings. In scenario 1, clearer and without any spacing between buildings, the values are higher than in other scenarios. The major disturbance of the flow in other models in which the urban form varies tends to reduce the intensity of the wind and, consequently, the pressure field on the facade. A negative pressure zone on the rear facade behaves as expected since it corresponds to a region of vortices and deceleration of the flows.

The increasing complexity in the geometry of each scenario produces more turbulent flows. However, the values not necessarily decrease when increasing density levels. As in the case of scenario 4 (160 inh/ha), the acceleration of flows between the surrounding buildings, which are taller (6 m), generates a higher pressure field on the model building facade when compared to scenario 3 (80 inh/ha). This is in part responsible for higher Cp values on the windows of the first storey.

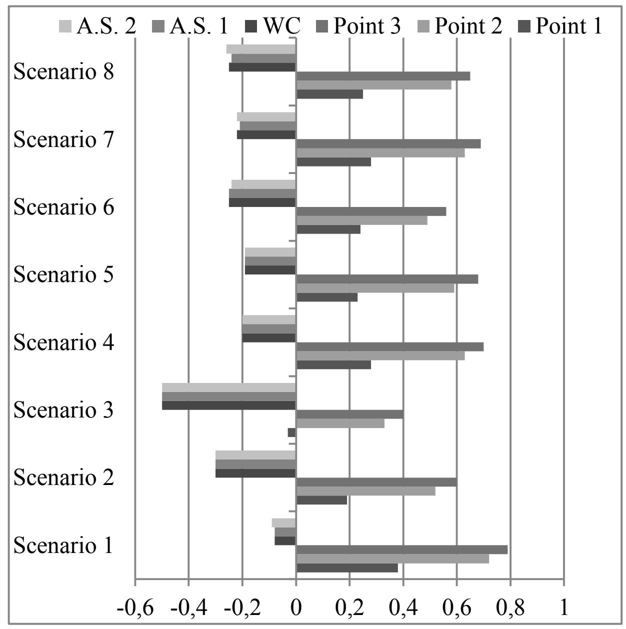

Figure 3: Cp values for east wind at the first floor

Increasing the height of buildings but maintaining the same distance between them produces a narrowing effect that creates a small urban canyon as highlighted in figure 4. This elevates the pressure field on the main façade in scenarios 7 and 8 when compared to scenarios 4 and 5. The higher air velocities within this space between buildings reinforce the higher pressure field.

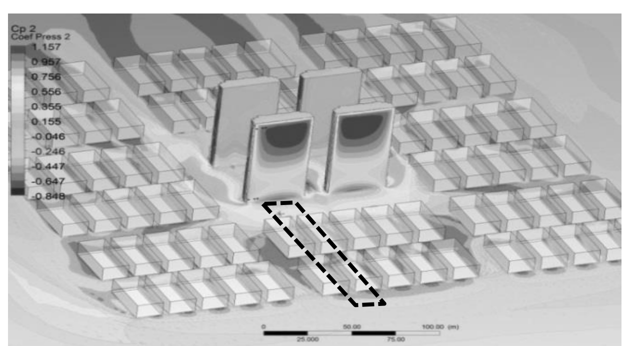

Figure 4: Acceleration of the flow between buildings increasing pressure incidence on the main façade.

For the twenty-third floor, Cp values are higher compared to first floor results. This is expected since the influence of ground roughness is less sensitive. As occurred with the results for the first floor, pressure field tends to reach higher levels as they deviate from the building corners, where the edge effect decreases the influence of air flow incidence.

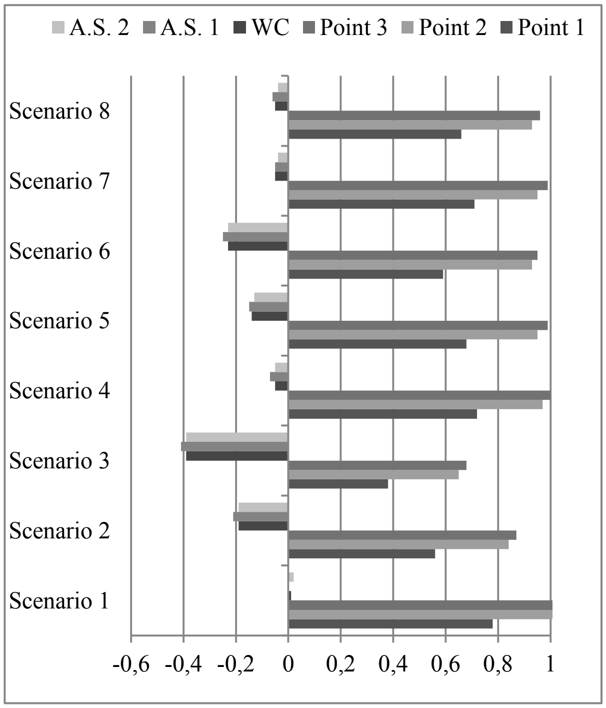

Figure 5: Cp values for east wind at twenty-third floor

An area of positive values on the leeward facade in scenario 1 was assessed using a vertical plane as a cross section in this specific area. As it´s possible to see in Figure 6 that there is a recirculation zone located in the vortex region between the first and second building. This particular effect directs a part of the flow upwards, while minimizing the intensity of the suction zone in the upper part of the building´s rear façade. Thus, it results in lower but positive Cp values (0.01 and 0.02) on the windows located in the rear façade at the twenty-third floor. The suction zone in the lower part of the building is more evident, generating an area of negative Cp values between -0.10 and -0.50.

Also, in other scenarios this very effect is responsible for the diminishing the negative Cp values at rear façades of the model building.

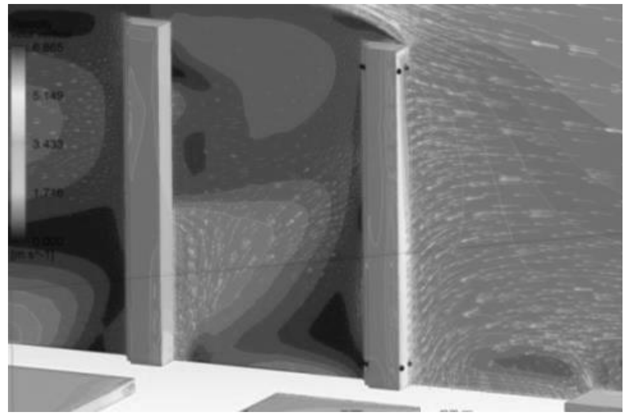

Figure 6: Vortices in downwind area redirecting the flow upwards

The position of the windows of the residential units evaluated, which are located in the left corner of the building model, indicate higher Cp values for southeast wind incidence comparing to the east wind.

Although the region in which higher Cp values are located is significantly smaller when compared to the east wind incidence, this specific area is precisely located right over the evaluated windows, which is responsible for higher Cp values compared to orthogonal incidence (east wind), as one can see in figure7.

In general, the more complex urban occupation gets lower Cp values are registered, as expected. The results get lower since scenario 2 but reach lowest levels at the third scenario where the density is relatively low, but higher change in air flows due to the larger spacing between buildings.

The narrowing effect that accelerates the flow between buildings in east wind incidence doesn't show the same intensity for 135° wind incidence.

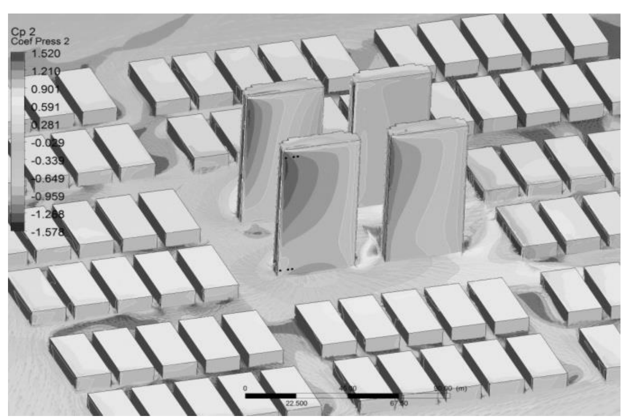

Figure 7: Concentration of higher Cp values zone close to the corner of the model building in southeast wind incidence

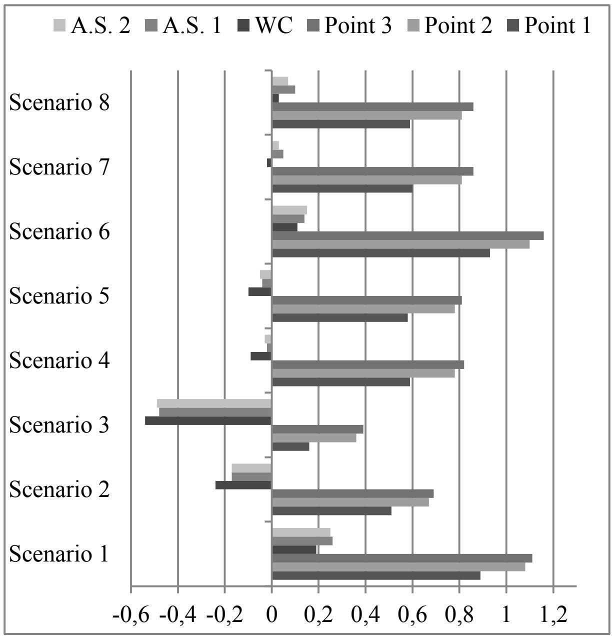

Figure 8: Cp values for southeast wind at the first floor

Cp values at twenty-third floor are even higher as expected due to reduction of roughness effect. A little variation in Cp values on windward façade (points 1, 2 and 3) even with higher density urban scenarios (scenarios 4, 5, 6 and 8) possibly indicate high air flow rates since Cp values are between 1.0 and 1.2, specially in higher residential units.

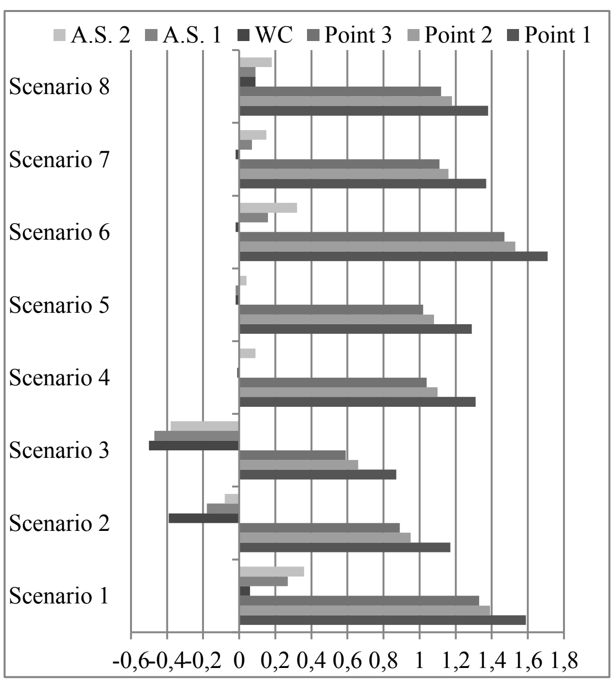

Figure 9: Cp values for southeast wind at twenty-third floor

For south wind incidence, negative Cp values are registered. Once air flow strikes building´s sidelong facades the wind deviates creating a downwind area. Thus, away from the windows located on the main facade, creating a zone of suction due to vortices located near the corners of the building.

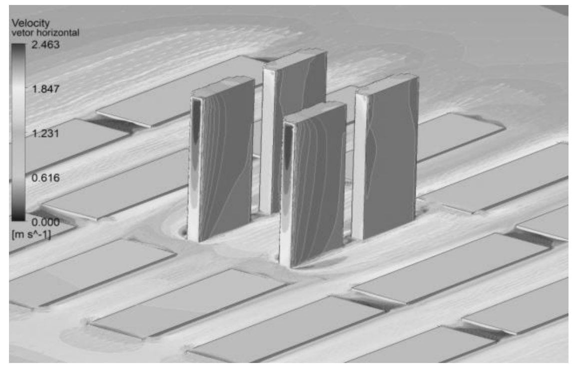

Figure 10: Pressure incidence for south wind

Specifically at point 1 on the first floor, negative Cp value is registered. Surrounding buildings seem to deviate the airflow, creating higher pressure zones at lower storeys as there aren´t many negative Cp values for points 2 and 3 as in the twenty-third floor. Reinforcing this effect, at lower storeys negative Cp values in point 1 tend to become positive with the increasing in the height of surrounding buildings and higher density levels, as in scenario 5, with Cp value from -0.14 and at scenario 8 the value reaches 0.25.

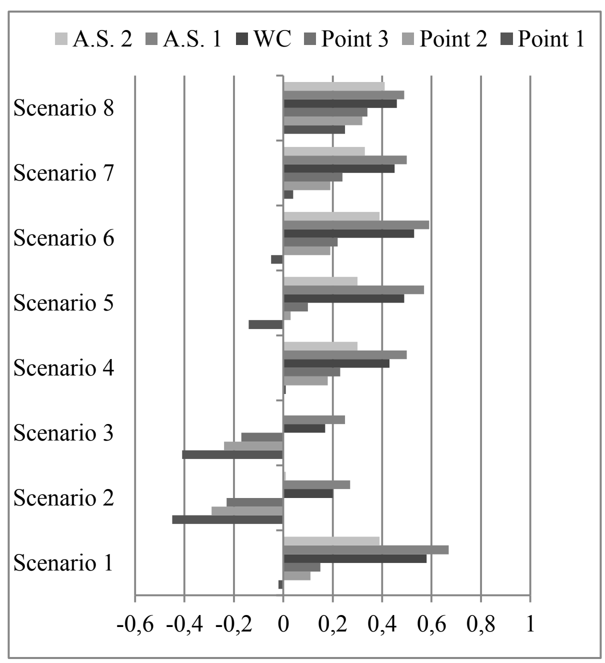

Figure 11: Cp values for south wind at the first floor

Also, building geometry plays major role on Cp values. The specific characteristics and form of the leeward facades significantly modifies the air flow around points 5, 6 and 7 for both first and twenty-third floor. At point A.S. 1, which is perpendicular to wind blowing from the south, indicates higher Cp values.

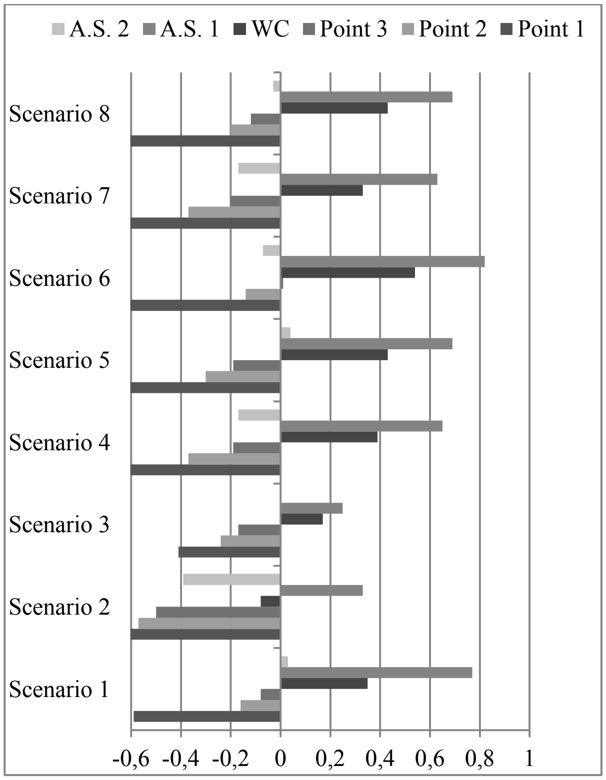

Figure 12: Cp values for south wind at twenty-third floor

CONCLUSION

Results reinforce the need to evaluate the CPs for each specific urban setting, since the surrounding obstacles are significant changes in pressure incident. It is possible to realize also the vertical rise in the speed profile with increasing height of buildings.

Some results require revision since comparing Cp values from one scenario to another highlighted some data that are significantly high or extremely low. It should be noted, however, that the verification of Cp values should always be accompanied by the analysis of the flow characteristics in vertical and horizontal planes.

Finally, pressure data obtained in this part of the research about urban densification and natural ventilation will be applied as input for the analysis of indoor air flow, both from the point of view of thermal performance (air flow rates) and velocity field. Thus, it becomes critical the improvement and validation of procedures in order to organize future simulations and producing accurate results.

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