Evaluating thermal performance of residential buildings in different urban environments:

Discussing a methodology to assess the impacts of densely built-up areas on indoor conditions

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ABSTRACT: Building simulation is applied to evaluate impacts of urban densification on indoor thermal conditions. In hot-humid climate regions such as the city of Fortaleza, in Brazil, building´s thermal performance is majorly affected by envelope design, cooling strategies and surrounding environment. Using a high-rise 24 storey model building in the centre of six different urban arrangement scenarios, urban density is assessed in terms of total discomfort hours and airflow rates within six rooms of two apartments in different heights. The methodology applied is presented and preliminary results indicate the direct impact of urban geometry on dwelling´s thermal performance. Need for higher ventilation rates are minimized by solar obstruction caused by surrounding buildings.

Keywords: building simulation, thermal performance, indoor comfort, cfd.

INTRODUCTION

The simulation of thermal and energy performance of buildings allows the evaluation of design process and architectural alternatives thru technical decisions such as site orientation, building components, materials, thermal inertia, lighting systems and air conditioning. These elements have significant impacts on indoor environment and energy consumption for building operation. In this context, software and energy performance of building models are important tools to calculate, in a relatively fast and simple way, the best solution to increase energy efficiency [1, 2, 3].

However, evaluating the energy performance of buildings depends on several factors, which are related with local climate context [1]. Besides local climate, surroundings play an important role in indoor environment conditions [2] once key elements such as obstructed radiation and the modification of wind induced natural ventilation are significantly changed due to urban development process.

Natural ventilation and solar radiation control are main passive design strategies to moderate internal temperatures, improving thermal comfort of building´s occupants and reducing energy use in hot-humid regions [4]. In the city of Fortaleza (3° 43’ S), in Brazil, building´s thermal performance is majorly affected by envelope design, cooling strategies and urban environment conditions. Nevertheless, little attention is given to the impacts of urban environment on wind pressure on building´s facades and physical obstructions reducing direct solar gains.

Densely built-up areas have the potential to compromise or enhance natural ventilation performance of buildings once its surroundings play a major role in pressure distribution on buildings façades. On the other hand, physical obstruction might reduce solar incidence at external surfaces.

Currently, a significant number of developing countries are in the tropical zone, where high temperatures and humidity are often reached during daytime. Climate conditions and recent populations´ increase in the purchasing power lead to greater use of air-conditioning, often seen as the only means to reach thermal comfort [5].

The present research intends to characterize the impact of different urban environments on thermal performance in dwellings located in a hot-humid climate city. This study focuses on assessing natural ventilation´s effective potential to maintain indoor thermal conditions and the role of surrounding urban environment as physical obstruction to solar radiation.

In this paper, first stages of this on-going research and methodology applied to evaluate urban densification and indoor thermal conditions are discussed as well as some of the preliminary results are presented.

DISCUSSING PART OF THE METHODOLOGY

Running transient CFD simulations of heat transfer and natural ventilation for the urban stretches presented in this research and also for the high-rise apartments evaluated may not be feasible in terms of time and computational resources available.

Therefore, airflow and thermal simulations were decoupled. Firstly, in a previous step, isothermal, steady-state and turbulent CFD simulations of the wind field for several building clusters were performed. These so called up scenarios were modelled using urban legislation standards such as building´s height, space between buildings and site coverage for the city of Fortaleza. The objective is to use maximum zoning practices to densely build up possible urban scenarios for the city and evaluate resulting indoor thermal conditions.

Within the current zoning practice for Zone for Priority Occupation (ZOP), nine typical urban blocks (100 m x 100m) were distributed in a 3 x 3 array. At the central block four high-rise residential model buildings (24-storey) were located. In the other eight blocks, land occupation varied in order to test different urban arrangements and morphologies.

Scenario 001 represents 160 inhabitants (inh) per hectare (ha) (figure 1a). A second situation (scenario 002) expresses around 320 inh/ha (figure 1b). A third scenario proposes 80 inh/ha (figure 1c) while the fourth scenario reaches the lowest urban density relation with 40 inh/ha (figure 1d). Then scenarios 007 and 008 express higher urban density values, reaching 480 inh/ha and 640 inh/ha, respectively (figure 1e and 1f).

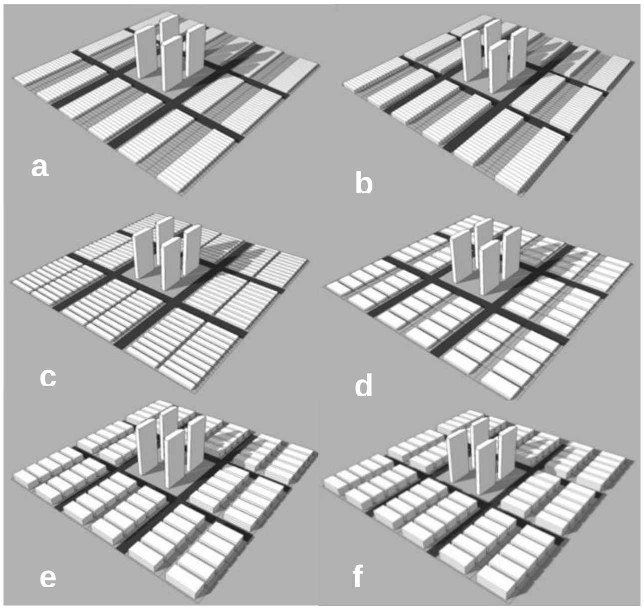

Figure 1: Six urban density scenarios assessed in terms of natural ventilation and thermal performance

Each of these six different urban arrangements were modelled in CAD and submitted to a commercial CFD code (ANSYS-CFX 14.0) to calculate pressure coefficients (Cp) on model building´s façades. The aim is to supply boundary conditions for thermal simulations thru the calculation of Cp values at each opening position. This decoupled methodology is applied in order to reduce simulation time and costs [6, 7, 8].

Cp is a key parameter in the study of wind induced natural ventilation and input data for several building simulation programmes, namely EnergyPlus. Commonly, building simulation programmes assimilate Cp database [9, 10] developed for general situations using simple or no adjacent obstacles or adopting simple terrain roughness effect. However, using general Cp data for the present research is not possible due to unique urban morphologies evaluated in each of the scenarios, which might lead to significant errors in airflow rate calculations and misunderstanding thermal analysis.

Once Cp values are calculated for specific urban configurations evaluated, thus thermal performance was simulated by geometric three-dimensional models using one of the four high-rise model building located in the centre of these low to medium urban density scenarios. Hourly values of indoor air temperature for flats are analysed using Cp as input data and weather data.

BUILDING SIMULATIONS PERFORMED

Thermal performance of the model building was carried out by means of DesignBuilder programme. This particular application is a user-friendly graphical interface for a widely used thermal balance engine: EnergyPlus [11].

DesignBuilder allows the dynamic evaluation of heating and cooling consumption during all year, including the complete EnergyPlus HVAC package. Also, the software has an easy to access meteorological database and a sophisticated model to evaluate energy supply for internal and solar energy supply [1].

In order to reduce large output files generated thru thermal simulations, only the apartments of the first floor, situated at 3 m height, and twenty third floor, situated at 66 m height were modelled in detail. Southeast orientated units were chosen due to a maximum solar exposure during the year for the city of Fortaleza, which leads to critical thermal conditions.

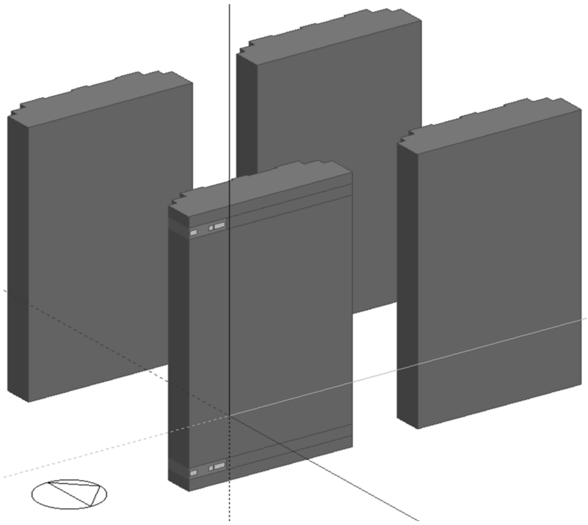

Figure 2: Isometric view of the model buildings located in the central block at each of the four different scenarios

Each of the two apartments analysed is occupied by a family of four. Building´s external walls have ceramic coating (U = 2,356 W/ m².K) while internal walls are masonry (U = 2,472 W/ m².K). Single clear 3 mm glass is applied to each of the windows (U = 5,89 W/ m².K) and solar factor of 0,86.

The main dormitory (Maindorm), dormitory 1 (Dorm_01) and living room (Livingroom) in each of the two apartments are isolated in thermal zones and evaluated in terms of indoor conditions (internal air temperature within the comfort zone) and natural ventilation performance (airflow rates).

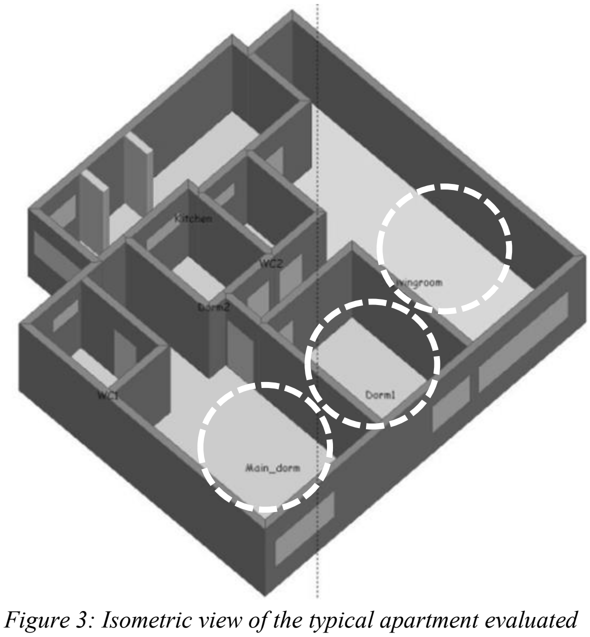

Figure 3: Isometric view of the typical apartment evaluated

EnergyPlus couples zone heat balance with zone airflow balance using an approach in which thermal and airflow model iterate within each time step until satisfactory small error estimates are achieved [12]. Simulations were performed applying its Conduction Transfer Function (CTF); detailed surface convection algorithm for the inside and the DOE-2 algorithm to calculate outside surfaces convection. For each simulation, four time steps were required in order to produce accurate results.

In EnergyPlus, ventilation rate driven by wind is given by Eq. 01 [12]. It is seen that the volume flow rate (V_{wind}) depends on the opening effectiveness (O_w), the opening area ($A_{opening}$), a multiplier fraction schedule ($F_{schedule}$) and the wind speed (S_w).

$$V_{wind}=O_w x\ A_{opening} x F_{schedule} x\ S_{wind} \qquad \text{(Eq. 01)}$$

An open window represents an aperture in a façade of a building and EnergyPlus recognises it within a net of pressure nodes. Within each apartment evaluated all windows stay open during all day thru the whole year. 50% of total area is used for naturally ventilate rooms.

In EnergyPlus opening effectiveness (O_w) is calculated for each time step based on the angle between the actual wind (α_{wind}) direction and the effective angle ($\alpha_{effective}$) of the wind entrance, as indicated by Eq. 02 [12].

$$O_w=0{,}55+\frac{|\alpha_{effective}+\alpha_{wind}|}{180}\ x\ 0{,}25 \qquad \text{(Eq. 02)}$$

The difference between the effective angle and the wind direction should be between 0 and 180°.

ASSESSMENT OF THERMAL PERFORMANCE

Measurements of thermal variables or HVAC energy consumption are commonly used to assess thermal performance of buildings. These are standard output data from building´s thermal performance simulation.

For free-running buildings such as the one evaluated in the present research, indoor air temperature is assessed together with an adaptive comfort model evaluation. However, assessment based on thermal comfort variables depends upon the determination of a comfort zone, indicated by the limits in which people may feel comfortable with the thermal environment.

Humphreys [12] adaptive model is applied due its better relation to local climate among others. This particular model was used to evaluate thermal comfort response within three thermal zones in dwellings of the first and twenty-third floor.

In his adaptive model, Humphreys [12] plotted indoor comfort temperature against outdoor monthly mean temperature from a number of surveys conducted world-wide. Thermal neutrality (Tn) is a temperature in which, on average, most part of people would feel neither hot nor cold in relation to outdoor average dry bulb temperature (To) as indicated by Eq. 03.

$$Tn = 0{,}534 \times To + 11{,}9 \qquad \text{(Eq. 03)}$$

For the present research, a comfort zone was set within a range of 1 degree higher and 1 degree lower than the neutral temperature from this model. These restricted limits are adopted once high levels of relative humidity are often reached by local weather.

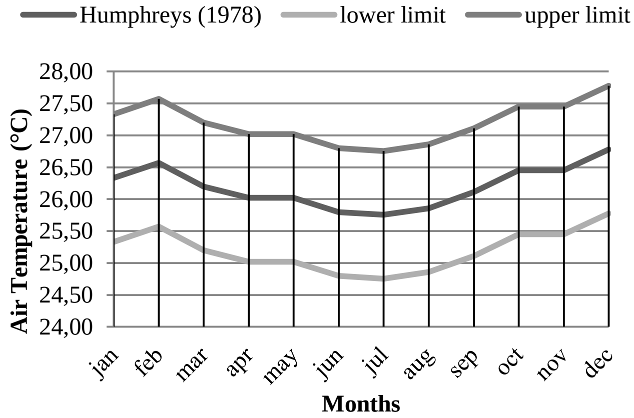

Figure 4: Upper and lower limits for Humphreys (1978) adaptive model and monthly mean temperatures for Fortaleza.

Total hours of discomfort within a typical meteorological year (TMY) weather data of 8.760 hours are the basis of analysis for each of three thermal zones assessed. Comparisons between the first floor apartment and the twenty-third one are also discussed.

PRELIMINARY RESULTS OF SIMULATIONS

In general, preliminary results emphasize the difference in total discomfort hours between first floor thermal zones and the ones at twenty-third floor.

Total discomfort hours in Maindorm at first floor are around 70% while at twenty-third floor is around 46% within the range of 8.760 hours. For Dorm_01 at the first floor total discomfort hours are around 61% of the period analysed while in the twenty-third floor the amount is lower: 46%. In the case of Livingroom, the thermal zone at the first floor has about 56% of the period outside the comfort zone while for the Livingroom at twenty-third floor has 44% of total amount of hours outside the comfort zone.

These results reinforce the role of natural ventilation to reduce total discomfort hours once at higher apartments such as the one in the twenty-third floor airflow rates tend to reach higher levels even if solar gains are higher. During the day, airflow rates reach differences from 17% to 85% for same thermal zones situated in different heights, attesting the influence of ground roughness in reducing wind pressure.

However, within a single thermal zone in different scenarios airflow rates values are very close from one urban arrangement to another. This, in turn, allows evaluating the role of solar gains for diminishing total discomfort hours particularly for first floor apartment and its thermal zones in scenarios 007 and 008, in which surrounding buildings have heights of 9 m and 12 m, obstructing solar incidence in first hours of the day.

Maindorm thermal performance is significantly influenced by Cp values, which in turn are modified by airflow close to building´s edge, where its window is positioned. Although, for the first floor, it is interesting to notice that scenarios 007 and 008 reach urban density levels of 480 inh/ha and 640 inh/ha and total discomfort hours registered are lower than the total amount for scenarios 001, 003 and 005. In these cases, urban density levels are significantly lower than scenarios 007 and 008, around 40, 80 and 160 inh/ha.

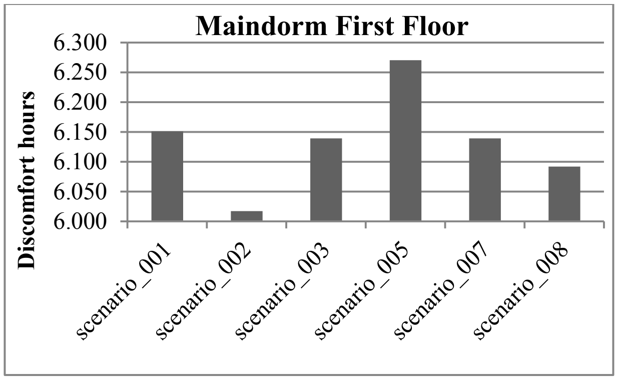

Figure 5: Total discomfort hours for Maindorm at first floor.

Lower results for main dorm at first floor in scenarios 007, 008 and also in scenario 002 reinforce the shadowing effect that is responsible for the diminishing of total discomfort hours. As one can see, surrounding buildings with 6 m, 9 m and 12 m in scenarios 002, 007 and 008, respectively, obstruct solar incidence for the first hours of the day. This is particularly important once in this period solar incidence is almost perpendicular to vertical surfaces of the main building. Even the lower wind pressures at openings which lead to lower airflow rates can´t compromise a better thermal performance than for scenarios with lower urban density values. Surrounding buildings in scenarios 002, 003 and 005 have 3 m height and therefore don´t obstruct any solar incidence at model building´s façades.

For dorm_01 in the first floor, shadowing caused by surrounding buildings seems to reduce total discomfort hours as in the case of Maindorm. Scenarios 001 and 002 have higher Cp values which lead to high airflow rates but total discomfort hours of scenario 007 is close to the amount of total discomfort hours registered in scenario 001. Again, in scenario 008, total discomfort hours reach the lowest value among other scenarios regardless airflow rates, which are low due to turbulent conditions generated by surrounding buildings´ height.

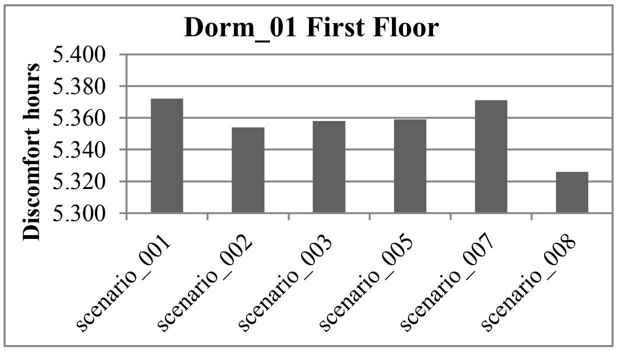

Figure 6: Total discomfort hours for dorm_01 at first floor.

Livingroom results for the first floor reinforces the role of shadowing effect in reducing total discomfort hours, as observed in Maindorm and dorm_01 cases. Despite slightly lower airflow rates, shadowing effect is responsible for reducing total discomfort hours in scenarios 007 and 008.

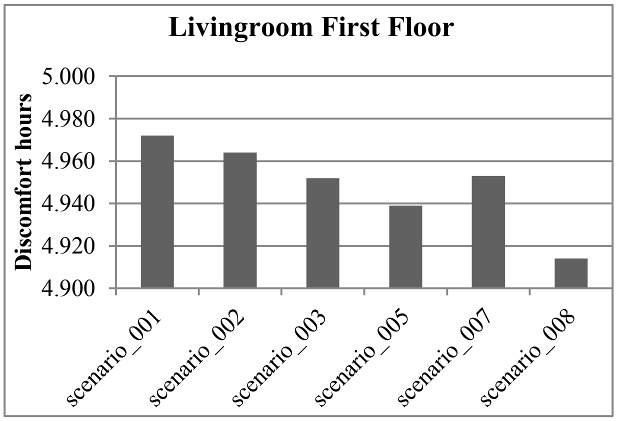

Figure 7: Total discomfort hours for Livingroom at first floor.

Analysing a typical summer day (19/02), when air temperature and relative humidity reach higher levels, it is possible to see that for the Livingroom, the space between surrounding buildings becomes crucial to get higher airflow rates once its window is positioned close to model building´s middle area. Scenarios 003, 005, 007 and 008 have higher airflow rates at first floor due to 4 m space between surrounding buildings, creating a kind of canyon that elevates the pressure incidence on model building´s façade. This is particularly important in the case of scenario 005 once its surrounding buildings are about 3 m height and also have space between them, resulting in higher airflow rates.

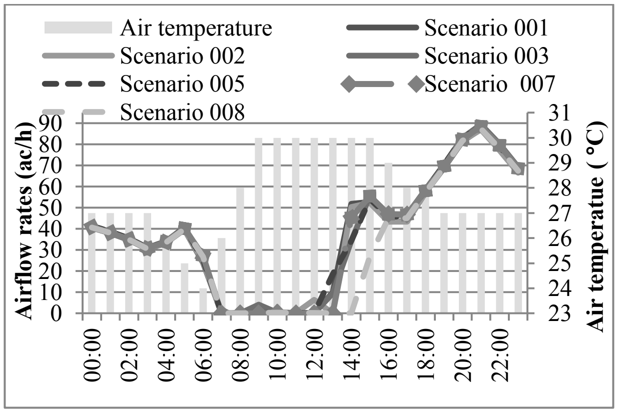

Figure 8: Air temperatures and airflow rates for a typical summer day in Livingroom.

Once at twenty-third floor there is no physical obstruction to solar incidence, results for all three thermal zones are close to each other within a range of 3.840 and 4.150 discomfort hours and highly dependent on airflow rates. Also, wind pressure is quite the same, once roughness effect becomes slightly noticeable. Airflow rates result directly from Cp variation that change accordingly to urban form (space between obstacles and building´s height).

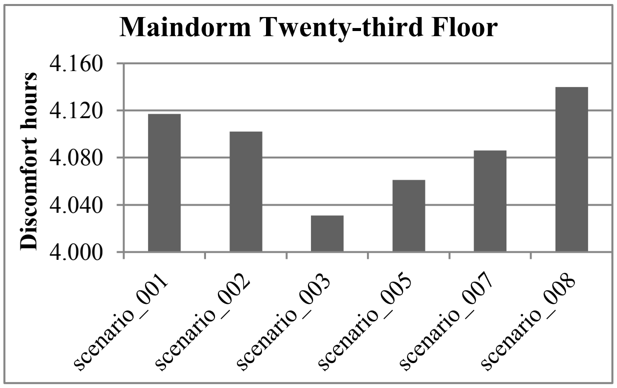

Figure 9: Total discomfort hours for maindorm at first floor.

Dorm_01 and Livingroom results at twenty-third floor are quite close to each other. In these cases discomfort hours are strongly affected by airflow rates, which tend to be lower in scenarios where surroundings have buildings about 9 and 12 m height (scenarios 007 and 008), reducing wind speed at higher levels.

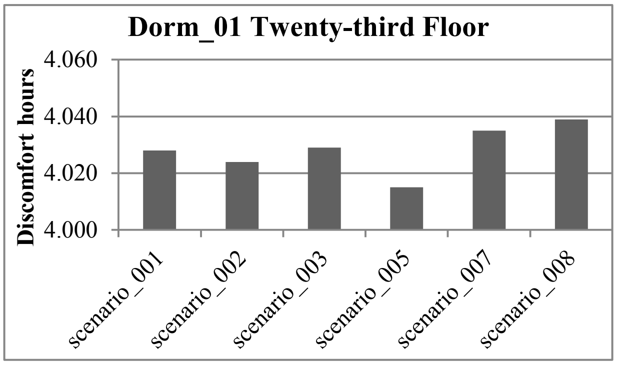

Figure 10: Total discomfort hours for Livingroom at twenty-third floor.

Airflow rates for dorm_01 are on average of 63 air changes per hour and doesn´t have a significant variation thru six scenarios, reducing around 4% from scenario 001 to scenario 008.

Livingroom results for twenty-third floor indicate airflow rates around 56 air changes per hour on average. On the other hand, elevation in height of surrounding buildings from scenario 001 to scenario 002 (3 m) reduces airflow rates around 2%. Increasing surrounding building´s height from 3 m to 9 m from scenario 005 to scenario 007 reduces airflow rates around 4%.

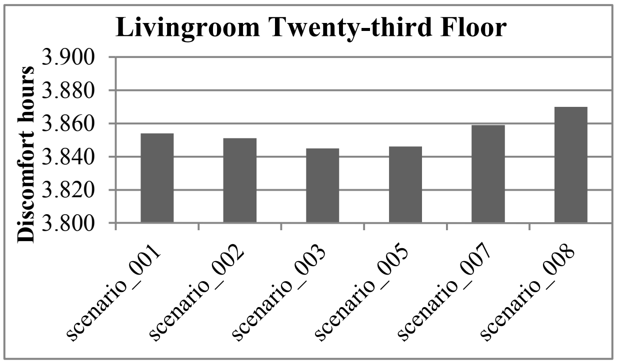

Figure 11: Total discomfort hours for Livingroom at twenty-third floor.

CONCLUSIONS

Natural ventilation is known as playing major impact on building´s indoor air quality and thermal comfort. However, the relation between building ventilation and thermal comfort depend on a large number of complex variables that need further investigations. Taking pressure coefficients as input data for building simulation also need validation.

Solar obstruction caused by surroundings plays an important role in urban densification as attested by results. Thus, it may be carefully assessed thru urban planning and development processes.

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