USE OF BUILDING THERMAL AND CFD SIMULATION IN THE DESIGN OF A LARGE OFFICE BUILDING IN LISBON

Daniel Albuquerque¹, Guilherme Carrilho da Graça¹
¹Instituto Dom Luiz, University of Lisbon, Lisbon, Portugal

ABSTRACT
This paper presents an application of building thermal and airflow simulation tools to the design of a naturally ventilated office building located in the center of Lisbon (Portugal). The seventeen-story building will have a hybrid ventilation system. The facade and natural ventilation system design were optimised using three interrelated simulation tools: Ecotect, EnergyPlus and PHOENICS (CFD). The dynamic thermal simulation (EnergyPlus) incorporated inputs from the other tools: the facade geometry was optimised using Ecotect and the wind driven airflow velocities that drive the single-sided natural ventilation system were obtained using CFD. The simulation results show that a carefully optimized building in Lisbon’s mild climate can operate in natural ventilative cooling mode for 70% of the year.

INTRODUCTION
The use of natural ventilation in services buildings has been slowly increasing in the last two decades. Many recent designs use a hybrid approach using natural ventilation in combination with traditional mechanical cooling and ventilation solutions. If properly implemented this combined approach maximizes the use of the natural approach while avoiding overheating during the warmer months and cold draft complaints in the colder days of the year.

The case study presented in this paper is the design and optimisation of a hybrid ventilation system for an office building in Lisbon. The natural ventilation system must meet the requirements of indoor air quality (IAQ) and thermal comfort of the recently updated Portuguese building energy performance requirements. The seventeen-story building has a height of 70m, a total floor area of 23000 m² and a small public park in the ground level. The surrounding area is mostly characterized by high-density and mid to high-rise buildings (see Figure 1). In the mild to warm climate of southern Europe services buildings without operable windows tend to require mechanical cooling during most of the year. This need is the direct result of high internal gains and, more often than not, poorly designed facades that allow for excessive solar heat gains. The building has an external skin shaped like an accordion, with vertical triangular fins (shown in Figure 2). This facade shape created particular challenges for the design team, namely:

- Positioning and sizing the ventilation openings.
- Defining which portions of the facade should be opaque or transparent.
- Defining the shading systems.

The design of the hybrid ventilation system was optimized using thermal simulations of several building façade configurations, choosing the configuration with the lowest energy consumption. The obstruction created by the new building is expected to increase ground level wind velocity creating the need for an outdoor wind comfort study. The inherent complexity of the natural ventilation systems created the need for a CFD simulations of...
the urban area that surrounds the office building. These simulations were also used to predict the air velocities close to facades that drive the wind-driven portion of the natural ventilation system.

This paper begins with an introduction to the applicable building regulations. The following section presents the simulation methodology, followed by a description of the procedures of each simulation tool, based on the best practices available in literature. The last section presents the discussion of simulation results.

**REGULATORY FRAMEWORK**

The project must comply with the Portuguese thermal code for services buildings with hybrid ventilation systems. The ground level assessment of outdoor wind comfort will be performed using the Dutch Standard for pedestrian wind comfort.

**Building codes**

The Portuguese legislation of building energy performance requirements was recently updated to conform with the European Directive 2010/31/EU, which is the main regulation tool created to assist E.U. countries in complying with international commitments (e.g. the 2020 strategy for EU member States and Kyoto Protocol).

According to this legislation a natural ventilation system must be able to maintain indoor CO2 levels below 1625 ppm for more than 90% of the annual occupied hours. The regulation defines a building as “hybrid” when the percentage of the annual occupied hours in which there are heating and/or cooling needs to maintain the indoor comfort temperatures of 19ºC - 27ºC is less than 30% (if less than 10% the building is considered “passive”).

**Pedestrian wind comfort criteria**

In the last decades, there has been an increase in clusters of high-rise buildings in the largest cities. In many cases, these clusters have generated problems of outdoor discomfort due to excessive wind velocity. Due to a lack of consolidated criteria in how to assess outdoor wind comfort will use the Dutch norm NEN-8100. Table 1 shows the criteria that are proposed by this norm for assessment of outdoor wind generated discomfort. For each location analyzed a wind comfort grade based on the annual probability of wind speed to exceeding a 5 m/s threshold velocity. Each wind comfort grade establishes three qualitative classes of comfort (good, moderate and poor) depending on outdoor activity levels (traversing, strolling and sitting).

**SIMULATION METHODOLOGY**

The interaction between the three simulation tools used in this study is shown in Figure 3. The need for a thorough evaluation of the solar incidence in the building skin was particularly clear in this project because the façade had multiple orientations that, initially, were all fully glazed. This analysis could have been performed in EnergyPlus but with much less flexibility in data visualisation. In this context, the 3D solar incidence analysis tool Ecotect was used to assess the solar heat gains in each orientation and define which orientations should be made opaque.

In the case of this building, natural ventilation is driven by a combination of wind and buoyancy. The building geometry and expected internal layout impose a single-sided (SS) natural ventilation strategy. SS wind driven ventilation can be modelled with engineering precision using the correlation (Warren et al., 1985):

\[ Q_w = 0.1 A U_L \]

Where \( U_L \) is the velocity parallel to the façade. In urban areas, this velocity depends on the local landscape, the shape and size of surrounding buildings and the building geometry. This correlation was implemented in EnergyPlus. In order to obtain the ratio between the undisturbed wind velocity (available in the weather data file) and the local

**Table 1 – Wind comfort criteria (NEN-8100).**

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Grade</th>
<th>Activity area</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW=0 m/s</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.1-1.0</td>
<td>A</td>
<td>Good</td>
</tr>
<tr>
<td>1.0-3.0</td>
<td>B</td>
<td>Good</td>
</tr>
<tr>
<td>3.0-10</td>
<td>C</td>
<td>Moderate</td>
</tr>
<tr>
<td>&gt;10</td>
<td>D</td>
<td>Poor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind danger</th>
<th>Wind comfort grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW&gt;1.5 m/s</td>
<td>Limited risk</td>
</tr>
<tr>
<td>&gt;2.0 m/s</td>
<td>Dangerous</td>
</tr>
</tbody>
</table>

- 2470 -

Figure 2 – Floor plan geometry.
velocity a set of CFD simulations were performed. The buoyancy-driven ventilation was calculated in EnergyPlus. The construction of a high-rise building in an urban area that was previously vacant, can result in an increase in wind speed at pedestrian level. To ensure wind comfort and wind safety for pedestrians, we also performed detailed CFD simulations around the adjacent park.

EnergyPlus was used to predict the building thermal and overall ventilation performance as well as size a mechanical conventional cooling and ventilation system that is used whenever the natural cooling by ventilation system cannot ensure thermal comfort.

This analysis evaluated incident radiation in three different heights (low, mid and high floors) of the main facades. For the south orientations a model with horizontal shading was also tested. The horizontal shading elements were defined as opaque thin plates with 95 cm length by 20 cm width, spaced from each other by 30 cm. The use of external shading in the East and/or West directions was not considered in order to preserve the external shape of the building since, in these cases, the shading elements would be vertical, due to low values of solar elevation angle, implying a modification of tower’s shape.

BUILDING SKIN OPTIMISATION (SHADING)

The first simulation analysis was based on a three-dimensional model of the building and all surrounding buildings that could shade the six building facades (see Figure 4 and Figure 5). The peculiar building skin results in two orientations for each façade. For example, the SE1 facade will South and East orientations.

Simulation Results

Figure 6 shows the impact in the yearly incident solar radiation in a façade with and without shading during the hot season (June to September). In this case the external shading elements reduce solar heat gains by 30%.
To determine the best solution for each facade orientation, an analysis based on annual incident radiation study was performed. The results of this study are shown in Figure 7. This study defined which orientation, in each façade, was opaque, or glazed, depending on the overall heats gains.

**CFD SIMULATION**

The CFD simulation used the commercial software package of PHOENICS, to predict airflow around and near the building facade.

**Geometry**

The geometry used in the CFD simulations included all the buildings within a radius of 200 meters from the office tower (Figure 8). This simulation domain size complies with the Architectural Institute of Japan (AIJ) guidelines for CFD urban environment simulations. The detail used in the CFD model varied between the office tower and surrounding buildings in accordance with the recommendations of Franke et al. (2007): the target building should be modeled with maximum detail while surrounding buildings can be modeled in an approximate way.

**Domain size**

The simulation domain size was defined based on the guidelines in the COST Action 732, that defined the best practices for CFD simulation flows in urban environments (see Figure 9):

- The domain height is $6H_{\text{max}}$, (were the maximum building height is $H_{\text{max}}$).
- The lateral boundaries are $5H_{\text{max}}$ away from the model boundaries.
- The inflow boundary from the area of interest is $5H_{\text{max}}$ from the first solid and the outflow is $15H_{\text{max}}$ away.

The flow blockage ratio is less than 3%, which is within the recommendations for CFD simulation.
Simulation objects and parameters

A total of eight CFD simulations were performed for the eight cardinal wind directions. For each wind direction, the neighbourhood/building model was rotated by 45° inside the domain. The simulations use the k-ε turbulence model, which has proven its robustness in this type of flows (Carrilho da Graça et al., 2012). A logarithmic wind inflow profile was used at the inlet with a wind speed of 10 m/s at a reference height of 10 meters (typical height for a weather station’s anemometer in a terrain with low roughness). The bottom of domain was set as a surface with an urban terrain roughness of 0.75 (Blocken et al., 2008).

In each simulation the average wind velocities generated near the façades and in the adjacent outdoor spaces were calculated in total of 23 planes. In the façade planes located in three heights (low, mid and high floors) of each main using a control surface spaced 30 cm from the wall and had a height of 4 m by a length of 10 m (spaning two adjacent offices). In the adjacent park, five control surfaces were distributed in North, East, South, West and center positions (see Figure 11). Table 2 shows the main characteristics of the simulation model.

CFD flow field

Figure 10 shows the CFD simulation results for horizontal and vertical wind speeds for incoming North wind. The figure clearly shows an increase in wind velocity near the southern tip of the building.

<table>
<thead>
<tr>
<th>Computational domain</th>
<th>1300m (x) x 1750m (y) x 540m (z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of interest (AI)</td>
<td>410 m (x) x 375 m (y)</td>
</tr>
<tr>
<td>Office tower height (H)</td>
<td>~ 70 m</td>
</tr>
<tr>
<td>Tallest bldg in AI (Hmax)</td>
<td>~ 90 m</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>173x184x107 (~ 3.4 million cells)</td>
</tr>
<tr>
<td>Expansion ratio</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>k-ε</td>
</tr>
<tr>
<td>Wind at reference height</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Reference height</td>
<td>10 m</td>
</tr>
<tr>
<td>Wind profile</td>
<td>Logarithmic</td>
</tr>
<tr>
<td>Wind directions</td>
<td>N, NE, E, SE, SW, W, NW</td>
</tr>
<tr>
<td>Blockage ratio</td>
<td>&lt; 3%</td>
</tr>
<tr>
<td>Iterations</td>
<td>5000</td>
</tr>
</tbody>
</table>

Figure 11 – Control surfaces distribution in office building and park (North view).

Table 2 – CFD simulation parameters.
OUTDOOR WIND COMFORT ASSESSMENT

The CFD simulations results allowed for the calculation of the ratio between wind speed at 10m and wind generated velocities in the adjacent plaza. For turbulent flow, this ratio is independent of flow velocity. The eight velocity ratios obtained for each of the five control surfaces are shown in Table 3.

Table 3 – Velocity ratios for eight wind directions considered.

<table>
<thead>
<tr>
<th>Control surface location</th>
<th>W</th>
<th>S</th>
<th>N</th>
<th>E</th>
<th>Centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.27</td>
<td>0.72</td>
<td>0.29</td>
<td>0.17</td>
<td>0.33</td>
</tr>
<tr>
<td>NE</td>
<td>0.53</td>
<td>0.38</td>
<td>0.50</td>
<td>0.39</td>
<td>0.46</td>
</tr>
<tr>
<td>E</td>
<td>0.44</td>
<td>0.31</td>
<td>0.67</td>
<td>0.22</td>
<td>0.52</td>
</tr>
<tr>
<td>SE</td>
<td>1.66</td>
<td>2.02</td>
<td>0.93</td>
<td>0.45</td>
<td>0.37</td>
</tr>
<tr>
<td>S</td>
<td>0.94</td>
<td>1.57</td>
<td>0.19</td>
<td>0.38</td>
<td>0.52</td>
</tr>
<tr>
<td>SW</td>
<td>0.97</td>
<td>0.62</td>
<td>0.27</td>
<td>0.35</td>
<td>0.68</td>
</tr>
<tr>
<td>W</td>
<td>0.84</td>
<td>0.85</td>
<td>0.72</td>
<td>0.85</td>
<td>0.47</td>
</tr>
<tr>
<td>NW</td>
<td>0.36</td>
<td>0.72</td>
<td>0.42</td>
<td>0.52</td>
<td>0.34</td>
</tr>
</tbody>
</table>

These ratios were applied to the typical mean weather year for Lisbon, generating five arrays of hourly air velocities. Finally, the statistic indicators defined by the NEN 8100 were calculated. The results are shown in Table 4.

THERMAL SIMULATION

The yearly thermal simulation was performed in EnergyPlus. This open source simulation tool has been proven reliable to simulate natural ventilation in buildings (Mateus et al., 2014), and has been previously used for single-sided natural ventilation (Wang et al., 2013).

The simulation model, shown in Figure 12, represents a typical floor of the building and has a total of 21 thermal zones (14 peripheral, 2 core office rooms, 1 circulation area, 1 corridor and 2 lifts, and 1 toilet). The office rooms have plasterboard walls, while circulation areas and toilets have concrete walls. The raised floor consists of floor tiles, non-ventilated air cavity and concrete slab. Finally, the ceiling is characterized by a plasterboard, a non-ventilated air cavity and a concrete slab.

Table 4 – Results of the pedestrian wind comfort assessment for the park zone.

<table>
<thead>
<tr>
<th>Control Surface</th>
<th>P (V&gt;5m/s)</th>
<th>Grade</th>
<th>P(V&gt;15m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>1.59%</td>
<td>A</td>
<td>0.00%</td>
</tr>
<tr>
<td>S</td>
<td>11.04%</td>
<td>D</td>
<td>0.00%</td>
</tr>
<tr>
<td>N</td>
<td>0.74%</td>
<td>A</td>
<td>0.00%</td>
</tr>
<tr>
<td>E</td>
<td>0.35%</td>
<td>A</td>
<td>0.00%</td>
</tr>
<tr>
<td>Center</td>
<td>0.14%</td>
<td>A</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

Table 5 – Internal gains depending of thermal zone.

<table>
<thead>
<tr>
<th>Internal Gains</th>
<th>Thermal Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perimeter</td>
</tr>
<tr>
<td>Occupants</td>
<td>15 m²/person</td>
</tr>
<tr>
<td>Lighting</td>
<td>7 W/m²</td>
</tr>
<tr>
<td>Equipment</td>
<td>15 W/m²</td>
</tr>
<tr>
<td>Fans&amp;Pump</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>Infiltration</td>
<td>0.3 ACH</td>
</tr>
<tr>
<td>Outdoor</td>
<td>24 m³/h.m²</td>
</tr>
<tr>
<td>Airflow Rate</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 – Simulation schedules considered.

<table>
<thead>
<tr>
<th>Occupancy, Lighting</th>
<th>Equipment</th>
<th>HVAC system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon - Fri 9am – 1pm</td>
<td>Mon - Fri 9am – 7pm</td>
<td>Mon - Fri 8am – 1pm</td>
</tr>
<tr>
<td>2pm – 7pm</td>
<td></td>
<td>2pm – 7pm</td>
</tr>
</tbody>
</table>

Loads and schedules

To complete the simulation model it was necessary to define the internal heat gains of each thermal zone and the building operation schedules (see Table 5 and Table 6). The lighting system was sized to maintain 500lux. To ensure indoor air quality when the windows are closed, outdoor airflow rates are set according to Portuguese legislation for offices rooms and not permanently occupied zones (RECS, 2013). Average fan loads were set according to the average table compiled by Westphalen et al. 1999.
**Thermal Simulation Scenarios**

The building optimization work evolved in the four steps presented in Table 8.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Fully glazed exterior facade</td>
</tr>
<tr>
<td>II</td>
<td>50% glazed exterior facade</td>
</tr>
<tr>
<td>III</td>
<td>Scenario II + South shading</td>
</tr>
<tr>
<td>IV</td>
<td>Scenario III + SS natural ventilation</td>
</tr>
</tbody>
</table>

The forth scenario has operable windows with a height of 1.5 m by 0.95 m of width. The net opening area of the window is 0.5 m² results in an opening to office floor area ratio of 3.8%. The thermal comfort temperatures of scenarios I to III were set at 20ºC – 25ºC. The last scenario had an extended range of 19ºC – 27ºC, that is recommended in the Portuguese thermal code for hybrid buildings.

The availability of the natural ventilation system varied according to the season, as shown in Table 9.

<table>
<thead>
<tr>
<th>Heating season</th>
<th>Natural ventilation system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon - Fri 9am - 7pm</td>
<td></td>
</tr>
<tr>
<td>Cooling season</td>
<td>Everyday 24h</td>
</tr>
</tbody>
</table>

**Results**

Table 7 presents the predicted HVAC energy consumption in each scenario at different heights. These results were averaged to obtain the results shown in Table 7 – HVAC energy consumption on each typical floor.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low floor</th>
<th>Mid floor</th>
<th>High floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat (H)</td>
<td>Cool (C)</td>
<td>H+C</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>45</td>
<td>47</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>IV</td>
<td>2</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>C</td>
<td>H+C</td>
</tr>
<tr>
<td>I</td>
<td>52</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>45</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>36</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>21</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H+C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td></td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>II</td>
<td></td>
<td></td>
<td>46</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td></td>
<td>36</td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

**Figure 13** (HVAC energy consumption for scenarios).

**Figure 13** – HVAC consumption for an averaged floor.

**CONCLUSION**

The combined simulation approach used in this study provided a significant contribution to reduce the uncertainties that are usually associated with natural ventilation systems. Accurate prediction of single sided natural ventilation airflows is difficult due to the dependance of the wind driven airflow on the local wind velocity parallel to the window plane. In order to incorporate this flow driving mechanism in a yearly thermal simulation the ratios between these velocities and the undisturbed wind velocity must be obtained using a wind tunnel model or CFD. In the analysis presented in this paper CFD is used to obtain these velocity ratios that are then incorporated into an Energyplus yearly simulation of a hybrid climate control system for an office tower.

This study uses a state of the art simulation approach that is not exempt from error and uncertainties. Thermal simulation of free running buildings has
been shown to result in average errors of up to 2ºK in both air and mean radiant temperature predictions. Further, the predictions single sided ventilation model were not adjusted for the peculiar building shape used in this project and, finally, the precision of RANS CFD when predicting wind driven airflow velocities near buildings with complex shapes has not been studied in detail.

The results indicate that, as expected for a narrow plan building, the natural ventilation system can maintain indoor air quality for 100% of the annual occupied hours. Yet, in order to maintain thermal comfort a mechanical cooling and ventilation system is needed for 24% of the occupied hours.

The overall building optimization process results in a 60% reduction in HVAC energy consumption (between scenario I and IV). The natural ventilation system is responsible for half of this reduction (30% of the HVAC energy consumption).

The pedestrian wind comfort assessment showed that 75% of the adjacent park area achieves an A grade classification (good). Unfortunately, the combination of the new building and an existing tower results in airflow acceleration near the Southern edge of the park where the predicted outdoor comfort index reaches D (moderate comfort for traversing).

ACKNOWLEDGEMENT
This research has been funded by the Fundação para a Ciência e Tecnologia (PhD grant: PD/BD/105995/2014).

REFERENCES


