Large Scale Modelling of Wind Comfort and Safety Using 'Pedestrian Comfort Analysis' - A Cloud-based App Crafted for Architects

Sandip Jadhav[1], Vijay Mali[1], Praveen Kumar Ramachandran[1], Chaitanya Rane[1]
[1]Centre for Computational Technologies, Pune, India

Abstract

Assessing the impact of building induced aerodynamics effects, on pedestrian comfort and safety, at a large scale is of great interest to local governments, architects, urban planners, designers, and developers. A common method of assessing pedestrian comfort is to perform a series of CFD simulations for different wind directions, combining the results with historical wind data obtained from the weather station near the site location and checking compliance with a suitable wind comfort criterion. The existing simulation tools and methodology demand CFD expertise and in-house high-performance computing facility. With the advent of powerful cloud computing, a new 'Pedestrian Comfort Analysis' application has been developed by simulationHub, that performs the CFD simulations on cloud and provides comfort and safety plots for large-scale models within hours. Through introduction and case study, this paper illustrates the 'Pedestrian Comfort Analysis' app to assess the pedestrian wind comfort and safety, across urban building design.

Introduction

Airflow and air quality is an important aspect of human comfort. Shape, height and the relative position of buildings can lead to changes in microclimates. A high-rise building considerably taller than the surrounding buildings tend to intercept the stronger winds at high elevations and redirect them downwards (Downwash), introducing high wind speed at the pedestrian level, which can lead to uncomfortable or even dangerous conditions. Funnelling effects can occur when the wind is accelerated by being channelled between buildings, often along pedestrian walkways.

Wise (1970) reported about shops that are left untenanted because of the windy environment which discouraged shoppers. Lawson and Penwarden (1975) reported dangerous wind conditions to be responsible for the death of two old ladies after being blown over by sudden wind gusts near a high-rise building.

Wind discomfort can be detrimental to the success of new buildings. It is beneficial to have known the potential impacts of a proposed development on the local microclimate early in the planning and design process as this allows sufficient time to consider appropriate wind control and mitigation strategies, including significant changes to the site and building designs. When buildings and sites are being planned, early-stage conceptual modelling can measure the risk.

Wind comfort and safety study

Pedestrian wind comfort and safety studies are conducted to predict, assess and mitigate the impact of the site and building designs on pedestrian level wind conditions. As a matter of fact, many urban authorities only grant a building permit for new high-rise buildings after the wind comfort study has indicated that the negative consequences for the pedestrian wind environment remain limited. The objective is to maintain comfortable and safe wind conditions that are appropriate for the intended use of pedestrian areas i.e., sidewalks and street frontages, pathways, building entrance areas, open spaces, amenity areas, outdoor sitting areas, etc. Pedestrian comfort analysis gives a basic understanding of how to mass and orient new buildings in the site location with existing surrounding buildings, to minimize the unwanted wind effects. It also gives an idea of what site elements like walls, trees, and landscaping can help improve the wind flow patterns on the site, to ensure the wind environment around the development allows safe and comfortable access for the pedestrians.

Studies of wind comfort and safety involve combining statistical meteorological data with aerodynamic information and a comfort criterion. The aerodynamic information is needed to transform the statistical meteorological data from the weather station (meteorological site) to the building site location. This transformed statistical data is then combined with the comfort and safety criteria to assess local wind comfort and safety. The wind comfort and safety criteria define a threshold value of the wind speed, and an allowed exceedance probability of this threshold. The aerodynamic information represents the change in wind statistics due to the local urban design. The building induced aerodynamics effects (i.e. the wind flow conditions around the buildings at the site location) can be obtained by either wind tunnel modelling or Computational Fluid Dynamics (CFD) simulations.

CFD has some important advantages compared to wind tunnel testing. Unlike wind tunnel testing, CFD study does not suffer from potentially incompatible similarity requirements because simulations can be conducted at full scale. This is particularly important for extensive urban areas. Wind tunnel measurements are generally only performed at a few selected points in the urban model and do not provide a whole image of the flow field. CFD, on the other hand, provides whole-flow field data, i.e. data at all the points of the computational domain. Thus, CFD simulations easily allow parametric studies to evaluate alternative design configurations at the early stages of development.

Challenges in conventional CFD software

Despite the above-discussed advantages, conventional CFD software have some challenges for the architect to use this technology in evaluating their building design.

Workflow and CFD software output

CFD simulation presents an efficient and comprehensive solution to predicting pedestrian comfort. A common method of assessing pedestrian comfort with computer simulations is to perform a series of steady-state CFD simulations for different wind directions, manually. A conventional CFD software can provide only the wind speed conditions at the pedestrian level in urban areas. Statistical analysis should be performed separately using a different code, to check compliance with various wind comfort criterion i.e. the simulation results for all the wind directions need to be combined to generate a comfort plot using a comfort criterion like Lawson, CSBT, BLWTL and NEN 8100.

CFD expertise

In CFD simulations, a large number of choices must be made by the user which can have a very large impact on the results. In a typical CFD simulation, the user has to choose the level of detail in the geometrical representation of the buildings, the size of the computational domain, the type and resolution of the computational grid, the boundary conditions, the approximate equations describing the flow (steady RANS, unsteady RANS (URANS), LES or hybrid URANS/LES), the discretisation schemes, the initialisation data and the iterative convergence criteria. Thus, the knowledge in CFD becomes a must for the architects to use CFD software to evaluate the design.

Computational time

Short time response is expected during the initial phases of design and development. In general, the desktop software uses the limited in-house computers to run all the CFD simulations. This may be time-consuming for a large scale (1km x 1km) area of urban simulation representing more ~15 to 20 million cells. With a standard setup, this means a computation time exceeding one day for each wind direction.

PCA - Cloud based web-app for architects

Pedestrian comfort analysis (PCA), the app from simulationHub addresses all the issues discussed in the previous section. The inputs required from the user are the building mass model, the site location, a nearby weather station and comfort criteria. All the other inputs related to CFD (computational domain, computational grid, boundary conditions, solver settings) are automatically generated by the algorithm. This lifts the main barrier for an architect to use CFD on their own, bypassing the traditional process of providing building design concepts to the simulation experts and then wait for the simulation results, to reiterate and improve the design. Even results of large-scale urban models (in sq. km.) are generated in few hours as the CFD simulations for all the wind directions are run in parallel mode, on the cloud facility.

The app directly gives the comfort plot as an output based on the comfort criteria selected by the user making it easy to understand and to make preliminary decisions. In addition, the 3D CFD results i.e. flowlines, velocity & pressure contours at different cut sections are accessible on the web browser for a deeper understanding of the flow behaviour around the buildings. Following are few such comfort plots generated by the PCA app, across various locations of 'The Hague' city in the Netherlands.

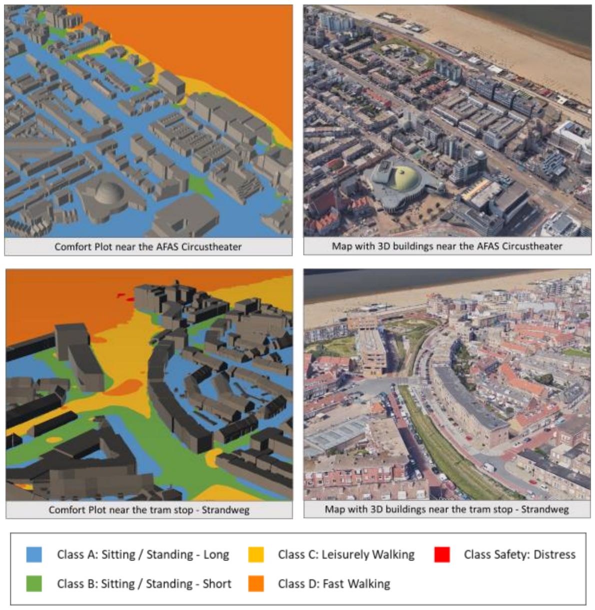

Figure 1: Comfort plot output from PCA app.

The comfort plot in Figure 1 shows the discomfort regions for standing (yellow and orange colour), near the tram stop – Strandweg, which is located next to the beach. This will help the urban designers to identify the problems and take necessary actions in planning the city. Aerial view of the maps showing the real-life 3D buildings is provided next to the corresponding results for comparison.

The user inputs and the CFD methodology followed in the app background are discussed in detail through a case study in the following section.

Case study: Empire State Building

The Empire State building is a 102-story skyscraper in Midtown Manhattan, New York City. The building has a roof height of 1,250 feet (380 m) and stands a total of 1,454 feet (443.2 m) tall, including its antenna. It is one of the tallest skyscrapers in the United States. The site of the Empire State Building is located on the west side of the 5th avenue between West 33rd and 34th streets. The building is surrounded by other multi-story buildings in all directions. An area of 1km x 1km considered for this study is shown in Figure 2.

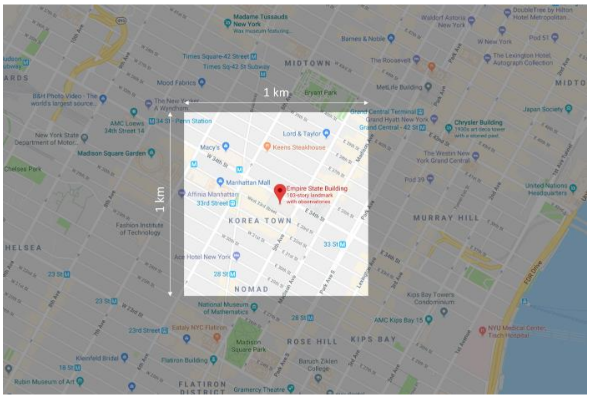

Figure 2: Study area around the Empire State Building.

User input 1 - Building geometry

Normally the distribution of buildings has the greatest impact on wind flow patterns. The level of detail required for individual buildings is dependent on their distance from the central area of interest. Buildings farther away may normally be represented as simple blocks. For the actual urban area, the buildings in the region to be assessed (generally 1–2H_{max} radius from the target building) should be clearly modelled.

Moreover, at least one additional street block in each direction around the assessment region should also be clearly reproduced as per Yoshie et al. (2005). COST (2007) suggest that the central building, at which wind effects are of main interest, requires the greatest level of detail.

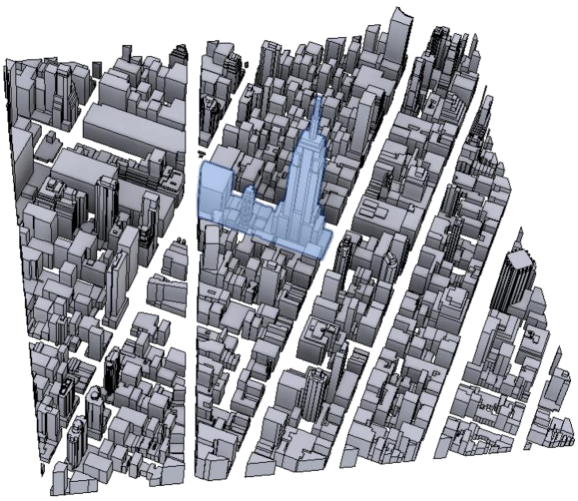

Figure 3: Building mass model (CAD).

The building geometry considered for this study is shown in Figure 3.

User input 2 - Site location and weather station

The buildings under study are located at Latitude: 40.75 and Longitude: -73.99. The location is highlighted using a red coloured icon in Figure 4. The user can select the site location through the map provided in the app.

Figure 4: Site location and nearest weather stations.

For analysis of wind behaviour, it is necessary to know the relevant wind data for the site. Selection of a proper meteorological data set is the key for any study involving wind data. The dataset should be from a weather station as near to the study location as possible. Wind data recorded at New.York-Central.Park weather station, supplied by TMY3 is used for the current study. The weather station is located within 2.32 miles from the actual site location (blue icon in Figure 4) and assumed to provide the best possible accurate representation of the wind conditions that site location is subject to.

California Energy Commission has released typical weather data sets including WYEC2, TMY2, CWEC, and CTZ2 as per Drury C (1998). Each of these datasets contains a year of hourly data (8,760 hours) synthesized to represent long-term statistical trends and patterns in weather data for a longer period of record. The user can either select the wind data from the weather station database or provide their own wind data. A "wind rose" diagram is the most common way of displaying wind data. It provides a graphical representation of how wind speed and direction are typically distributed at a particular location.

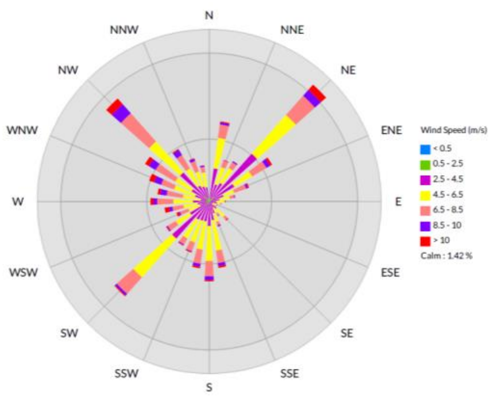

Figure 5: Wind Rose data at selected weather station.

The wind rose diagram for the selected weather station is shown in Figure 5.

User input 3 - Wind conditions

The user has the option of selecting the number of wind conditions to be considered for the CFD simulations. For this study, a total of 32 compass directions on the wind rose are selected for simulation. For each direction, the reference wind speed is set to 5% exceedance i.e. the wind speed that is exceeded for only 5% of the time. These wind speeds are shown in Table 1.

Table 1: Wind conditions used for CFD simulations

Condition Number	Wind Velocity (m/s)	Direction (°)	Frequency
1	5.33	45.00	9.11
2	6.01	315.00	8.02
3	5.00	225.00	7.39
4	4.93	11.25	4.72
5	5.43	180.00	4.65
6	6.16	303.75	4.33
7	5.39	56.25	4.25
8	5.44	191.25	3.93
9	5.53	168.75	3.90
10	6.29	292.50	3.70
11	5.75	326.25	3.55
12	5.90	270.00	3.42
13	5.04	202.50	3.15
14	6.44	281.25	3.04
15	5.00	213.75	2.99
16	4.95	236.25	2.91
17	4.76	33.75	2.73
18	5.31	337.50	2.67
19	6.17	258.75	2.63
20	4.89	22.50	2.57
21	5.55	67.50	2.45
22	4.97	348.75	2.13
23	5.87	247.50	2.02
24	4.81	157.50	1.55
25	5.10	78.75	1.53
26	4.99	135.00	1.50
27	4.89	146.25	0.99
28	4.71	90.00	0.96
29	4.26	101.25	0.73
30	4.74	112.50	0.51
31	4.82	123.75	0.49
32	3.62	0.00	0.07

User input 4 - Incoming wind exposure

As a standard practice, when assessing pedestrian level wind speeds, atmospheric boundary layer should be considered while defining the inlet wind velocity profile. Also, its behaviour is directly influenced by its contact with the surface. For example, the wind velocity profile passing through the ground and man-made obstructions on the ground are different from those passing over open sea water. The wind exposure settings used for the current study are shown in Figure 6.

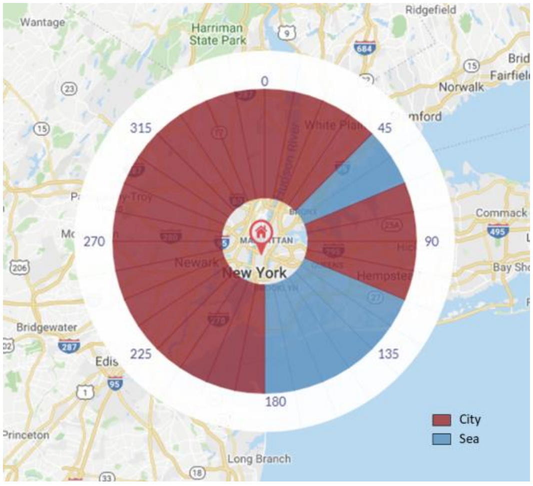

Figure 6: Wind exposure.

The details of the inlet wind velocity profile based on the selected terrain type are discussed in later sections of the paper that describes the CFD methodology used in the background of the app.

User input 5 - Comfort criteria

Comfort is truly a relative term and governed by the activity of pedestrian. The comfortable wind around a pedestrian running, might feel uncomfortable for the one standing or be sitting at a place for a long time. The behaviour of pedestrian and their expectations about comfort and safety is studied for many years. To assess the pedestrian comfort level and safety, there are standard criteria available like Lawson, CSTB (Scientific and Technical Centre for Building), BLWTL (Boundary Layer Wind Tunnel Laboratory), and NEN 8100 (Nederlandse Norm, Dutch standard).

In general, any comfort criterion is divided into two parts: pedestrian comfort criteria and safety criteria. Pedestrian comfort criteria are for regular activities like walking, standing, and sitting. This helps in determining the usability of a location or site against these activities. The criterion sets out threshold local air speeds based on the activity, which cannot be exceeded for more than specified percentage time of the year (usually 5% but varies for different criteria). The safety criterion stipulates the air speeds which cannot be exceeded a specified percentage time of the year, relatively very low value compared to that of comfort exceedance percentage. This ensures that pedestrians and cyclists are not in danger of physical harm from high airspeed.

For the current study, Lawson comfort criteria are selected to evaluate comfort levels. Table 2 shows the details of the threshold local air speeds based on the activity and the exceedance percentage i.e., threshold airspeed cannot be exceeded for more than exceedance percentage of the year.

Table 2: Lawson comfort criteria.

Class	Description	Velocity (m/s)	Exceedance
A	Sitting/Standing Long	> 4.0	<5.0 %
B	Sitting/Standing Short	> 6.0	<5.0 %
C	Leisurely Walking	> 8.0	<5.0 %
D	Fast Walking	> 10.0	<5.0 %
Safety	Distress	> 15.0	<0.0002 %

With the above inputs, the setup is complete and is ready for simulation on the cloud. The details of the CFD analysis methodology that runs automatically in the background of the app are discussed in the next section.

CFD analysis methodology

Although the further processes are automated, it is important to understand the general CFD process and the methodology used in the app before looking at the results.

Computational domain – shape and size

An outer domain representing virtual environment is generated around the building geometry in the shape of a polygonal prism with 32 sides. The same domain and the mesh would be used for simulation of all the wind directions.

The size of the entire computational domain in the vertical and radial directions depends on the area that shall be represented. VDI (2005) suggests a blockage dependent distance between the computational domain boundaries and the buildings, where the blockage is defined as the ratio of the projected area of the building in the flow direction to the free cross section of the computational domain. In the CFD community, a smaller maximum blockage of 3% is normally recommended, based on the results of Baetke et al. (1990) for the flow over a wall mounted cube.

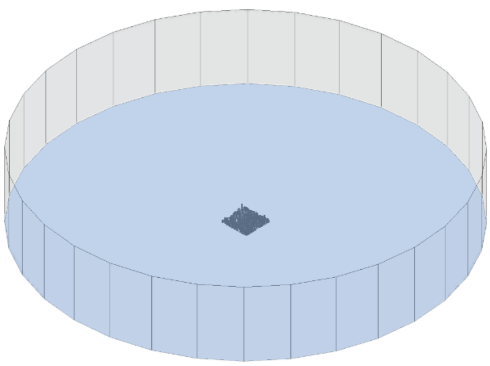

Figure 7: Computational domain.

In PCA, for urban areas with multiple buildings, the top of the computational domain is $5H_{max}$ away from the tallest building with height H_{max}. The radial size of the computational domain is minimum $2.5L_{bb}$ (L_{bb} is the diagonal length of the building bounding box) from the outer edges of the building geometry and extends up to a distance where the buildings included in the computational domain does not exceed the recommended blockage ratio (3%).

Computational grid

A CFD model requires the fluid domain to be divided into discrete elements (made up of geometric primitives like hexahedra and tetrahedral) or cells. The governing equations are then discretized and solved inside each of these cells. The collection of all these elements or cells is called a mesh or grid. The distribution of these mesh elements defines the level of accuracy.

In order to predict the flow field around a building with acceptable accuracy, the most important thing is to correctly reproduce the characteristics of separating flows near the roof and the walls. In PCA, a fine grid size arrangement is maintained to resolve the flows near the building corners. To reproduce the separation flow around the upwind corners, a cell size to accommodate a minimum of 10 grid cells is applied on the sides of each building, according to the cross-comparison results for a simple-building model by Mochida et al. (2002); Yoshie et al. (2005).

Additionally, the grids are arranged so that the evaluation height (1.6m above ground) is located at the 3rd or higher grid from the ground surface as suggested by Tominaga et al. (2005). Best practice guidelines of COST 732 Franke (2004) also recommends that pedestrian wind speeds at 1.5–2m height be calculated at the third or fourth cell above the ground. Four layers of prism cells are generated on the building walls and ground surface with hexahedral cells away from the wall. The position of the first computational node is placed in the logarithmic region, corresponding to a non-dimensional wall distance (y+) of 30 as suggested by Casey (2000).

For the current study, a mesh count of 17.3 million cells is generated by the PCA application.

Boundary conditions

The boundary conditions represent the influence of the surroundings that have been cut off by the computational domain. It defines the interaction between a simulation model and its environment. The ability of CFD simulation to converge on a solution is related to how well the boundary conditions are defined.

In the PCA application, four different boundary types are specified viz., inlet, outlet, symmetry and wall. Inlet and outlet boundary conditions are applied on the sides of the 32-sided polygonal prism-shaped outer domain. Out of the 32 faces, 16 inlet and 16 outlet faces are selected automatically based on the wind direction (vary for each simulation/wind condition).

Accurate specification of the boundary layer wind profile is crucial in correctly simulating the pedestrian level wind environment. For this reason, the below equation from ASHRAE Handbook – Fundamentals ch.16 (2005) is used, to create a wind boundary layer profile based on the which the wind speed increases with the height from the ground.

$$U_H = U_{met} \left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}} \left(\frac{H}{\delta}\right)^{a} \qquad (1)$$

The wind boundary layer thickness ‘δ’ and exponent ‘a’ for the local building terrain are determined from Table 3 taken from ASHRAE Handbook – Fundamentals ch.16 (2005).

Table 3: Atmospheric boundary layer parameter.

Terrain Category	Description	Exponent a	Layer Thickness δ, m
1	Large city centers, in which at least 50% of buildings are higher than 21.3 m, over a distance of at least 0.8 km or 10 times the height of the structure upwind, whichever is greater	0.33	460
2	Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 460 m or 10 times the height of the structure upwind, whichever is greater	0.22	370
3	Open terrain with scattered obstructions having heights generally less than 9.1 m, including flat open country typical of meteorological station surroundings	0.14	270
4	Flat, unobstructed areas exposed to wind flowing over water for at least 1.6 km, over a distance of 460 m or 10 times the height of the structure inland, whichever is greater	0.10	210

Typical values for meteorological stations, generally measured in flat, open terrain (category 3 in Table 3), are met = 0.14 and δmet = 270 m. For the current study, the user inputs from Figure 6 is used to select the values of ‘a’ and ‘δ’ from Table 3.

At the boundary behind the obstacles, open boundary conditions or constant static pressure are generally used. In PCA, an atmospheric pressure boundary condition is applied at the outlets of the domain. A no-slip wall condition is applied to all the buildings and ground surfaces. The top surface of the outer domain is given a symmetry boundary condition.

Simulation

Computational Fluid Dynamics (CFD) solves the Navier Stokes equations governing fluid flow over the computational domain. The direct solution of these equations would require the resolution of all the spatial and temporal scales which is not possible in most cases due to the resource and time limitations. This is simplified by averaging the basic equations to filter out the many scales of the turbulent flow and selecting a turbulent closure to model these filtered out scales.

In PCA application, the CFD simulations are performed using the OpenFOAM solver and by solving the 3D steady RANS (Reynolds Average Navier-Stokes) equations. The closure is provided by the realisable k-ε turbulence model. The choice for this turbulence model is based on the recommendations by Franke et al. (2004) and other successful validation studies for pedestrian-level wind conditions by Blocken et al. (2004), Blocken and Carmeliet (2008); Blocken and Persoon (2009). Pressure-velocity coupling is taken care of by the SIMPLE algorithm. The calculation needs to be finished after sufficient convergence of the solution. The judgement of the iterative convergence is normally based on the residuals, which indicate how far the present solution is away from the exact solution within each cell. COST suggests that scaled residuals should be dropped 4 orders of magnitude, Franke (2006). Beyond this point, the scaled residuals do not show any further reduction with the increasing number of iterations. Therefore, the iterations are automatically terminated when the solution falls below the set recommended convergence criteria. Air is the working fluid and the physical properties of the air at 20˚C are considered for the CFD simulations.

Results

The complete time taken for all the automated process discussed in the above section is 4 hours 23 minutes. Once the simulations are completed, the post-processed results are available on the web browser.

Building aerodynamics

The aerodynamic information used to generate the comfort plot are obtained using multiple steady-state CFD simulations for different wind directions. This section presents the results obtained from CFD simulations for different wind conditions.

The below images shows the velocity contours plotted on a plane located at ~1.6 m above ground, for first few of the wind conditions from Table 1. The corresponding wind directions are shown in the top right corner of the images.

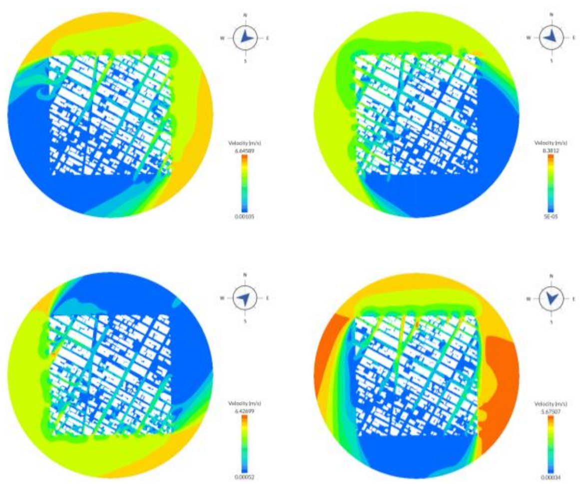

Figure 8: Velocity contours for wind conditions 1–4.

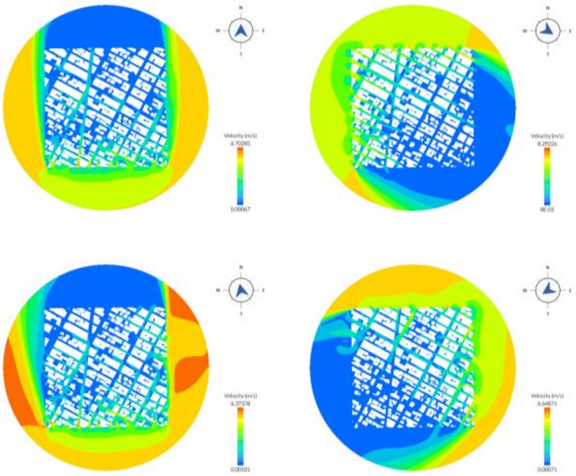

Figure 9: Velocity contours for wind conditions 5–8.

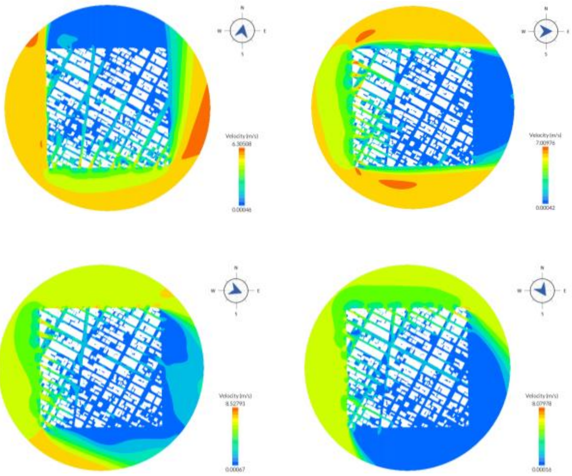

Figure 10: Velocity contours for wind conditions 9–12.

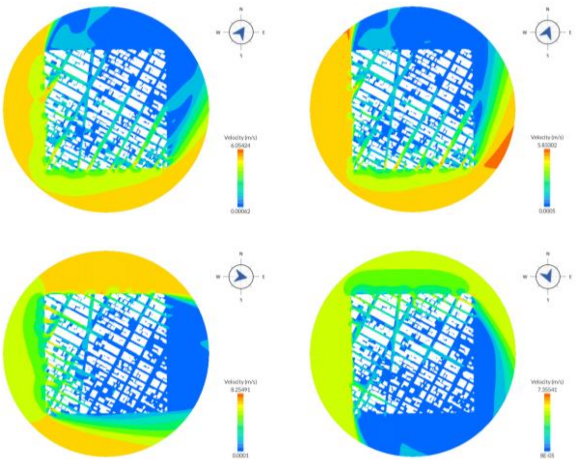

Figure 11: Velocity contours for wind conditions 13–16.

Please note that the above images show the velocity contours on a plane clipped to a smaller diameter to focus on the flow behaviour near the buildings.

Comfort plot

The steady-state CFD simulations of all 32 wind directions are scaled to the magnitudes of wind velocities from the weather data (from New.York-Central.Park weather station) in order to calculate the number of hours a year, each portion of the site has a wind velocity above the threshold specified by Lawson criteria. This allows predictions to be made on the suitability of different areas of the site based on the different pedestrian activities outlined by Lawson. Colour codes used in the comfort plots, to represent the activity comfort levels defined by the Lawson criteria are shown in Table 4 for reference.

Table 4: Colour code for Lawson criteria.

Class	Colour	Description	Velocity (m/s)	Exceedance
A		Sitting/Standing Long	> 4.0	< 5.0%
B		Sitting/Standing Short	> 6.0	< 5.0%
C		Leisurely Walking	> 8.0	< 5.0%
D		Fast Walking	> 10.0	< 5.0%
Safety		Distress	> 15.0	< 0.0002%

This section presents the assessment against the comfort criteria for class A, B, C, D and safety. Figure 12 shows the suitability of the different pedestrian areas for various usages. The assessment is made at 1.6m above ground level for the pedestrian areas.

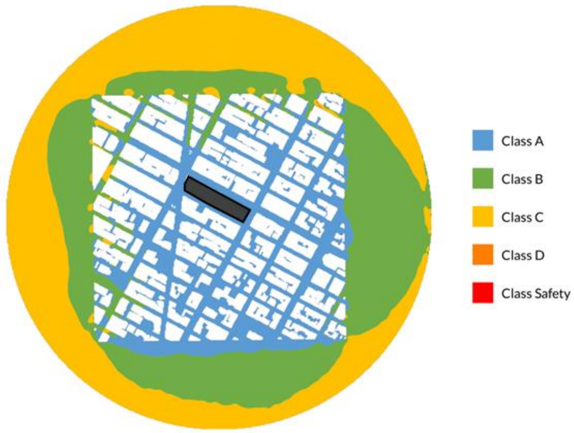

Figure 12: Comfort plot at 1.6m above ground.

The comfort plot shows most of the regions around the Empire state building, coloured with blue (class A), indicating that these areas are suitable for pedestrians to sit or stand for extended periods without experiencing discomfort due to wind effects.

Summary and conclusion

PCA, a cloud-based web application with automated CFD process, was developed for architects and urban designers to assess the wind comfort levels in urban environments. The paper has presented the numerical methodology behind the app to assess the wind pedestrian comfort in an urban area. With the use of powerful cloud computing, comfort plots of even large scale building models are delivered quickly to help urban designers in their early design phase. A case study is presented at the end of the paper to demonstrate the capabilities and advantages of the application for urban designers.

The application workflow and the case study in this paper is intended to show the CFD methodology used in the background of the PCA app in studies of wind comfort and wind safety with CFD.

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