On the Assessment of Wind Microclimate in a Complex Urban Environment Utilising Computational Fluid Dynamics

NEIHAD HUSSEN AL-KHALIDY
CFD, Wind, and Energy,
SLR Consulting,
Tenancy 202 Submarine School, Sub Base Platypus,
120 High Street, North Sydney 2060,
AUSTRALIA

Abstract: - This paper presents an insight and key considerations for using Computation Fluid Dynamics (CFD) to simulate the Wind Microclimate in a Complex Urban Environment. The current study involved developing a local 10m height "reference" wind rose for the project site and then combining statistical meteorological data with aerodynamic information and wind comfort and wind safety criteria. Where wind speeds were found to be at undesirable wind levels at areas of interest (ground level, podium level, terraces, balconies, etc.), recommendations were made to reduce detrimental wind effects, e.g. using landscaping, porous windbreaks, canopies, etc. The criteria used in the evaluation of pedestrian-level winds surrounding the proposed development were based on the well-established "Lawson" criteria which couple the probability of exceeding winds at given statistical levels with wind speed magnitudes originally related to the Beaufort Land Scale. To take into account the influence of the immediate surrounding environment, all neighboring buildings and local topography within a diameter of almost 1,000 m around the site were included in the developed CFD model. Furthermore, all small canopies, balconies, and semi-open spaces were modeled in detail as per the provided architectural drawings. Based on a mesh sensitivity assessment, polyhedral elements were used for the entire computational domain. CFD analysis offers a comprehensive range of output including the velocity distribution in three directions and turbulence levels, allowing the identification of hot spot areas that have potentially unacceptable wind conditions for further assessment and mitigation treatments to reduce wind speed to acceptable levels. The baseline (no mitigation) scenario simulation results contributed to a better understanding of the environmental wind impact for the project at the site, enabling a targeted approach to the development of effective windbreak options This paper provides a comprehensive approach toward the establishment of a robust CFD assessment of human comfort to ensure that proposed building developments and their streetscapes create a comfortable wind environment to live and visit.

Key-Words: - Pedestrian Wind Comfort, Balcony Wind Comfort, Wind Mitigation Treatment, CFD, Complex Urban Environment, Lawson Criteria.

Received: January 14, 2024. Revised: July 13, 2024. Accepted: August 11, 2024. Published: October 1, 2024.

1 Introduction

The construction of a new building inevitably changes the microclimate in its vicinity. Medium and high-rise buildings can create wind conditions that cause discomfort for pedestrians at ground level making public and private outdoor spaces potentially unusable. This includes footpaths, entrances, communal open spaces, terraces, balconies, and public-access rooftops.

Environmental wind impact studies are therefore mandated by urban authorities to ensure that publicly or privately accessible outdoor space within a new development or on surrounding streets will not have uncomfortable or potentially unsafe wind impacts.

Wind impact assessments are routinely carried out using wind tunnel testing or Computational Fluid Dynamics (CFD).

In the Netherlands, a standard for the assessment of wind comfort and wind danger was published in 2006, [1]. The City of London has provided a guideline for wind microclimate studies required as part of the planning applications of new development proposals. The guideline provides the specification of quality assurance requirements, both for CFD and for wind-tunnel testing, [2].

Several best practice guidelines have been established for wind engineering applications including the assessment of pedestrian-level wind environments, [3], [4], [5].

A review of wind tunnel and CFD techniques to determine pedestrian ground-level wind was presented in [6]. This study concluded that the use of low-cost wind tunnel techniques (e.g. Irwin sensors or sand erosion) and steady-state Reynolds-Averaged Navier-Stokes (RANS) simulations not necessarily compromise the accuracy of pedestrian-level wind comfort assessments due to their ability to provide accurate results (~10%) at high amplification factors (>1), even though their accuracy can deteriorate at lower amplification factors (<1). Amplification factors are defined as the ratio of local mean wind speed to mean wind speed at the same position without the building present. Higher amplification factors provide the largest contribution to the discomfort exceedance probability of the comfort criterion.

CFD predictions of wind flow around bluff bodies have been compared and validated against wind tunnel and full-scale measurements in the open literature, [7], [8], [9].

Through advances in processing power and numerical turbulence models, CFD analysis can be considered a promising numerical tool to help urban designers and environmental planners evaluate strategies of urban planning [10] and the design of better buildings, [11].

This paper presents insights and key considerations for using Computation Fluid Dynamics (CFD) to simulate the Wind Microclimate (pedestrian-level wind and balcony wind conditions) in a Complex Urban Environment.

1.1 Objectives of the Current Study

In contributing to existing literature, the current study

- Develop a 3D CFD model for a complex built environment including topography and detailed design features (canopies, façade articulation, vertical screens, etc.).
- Develop localized weather data for the project site and relate the CFD output to the local wind climate probability distribution to yield the frequency of occurrence of different wind events – ie scouring events - at appropriate probability levels, eg once per month, once per year, etc.
- Provide an integrated approach toward the establishment of a robust CFD assessment of human comfort in public and private open spaces.

2 Problem Formulation

The CFD model solves the continuity and momentum, equations. The equations for a steady-state case can be written as follows:

$$\frac{\partial}{\partial x_i}(\rho\, u_i) = 0$$

$$\frac{\partial}{\partial x_j}(\rho\, u_i\, u_j) \;= -\; \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}) + \rho\, g_i + F_i$$

In the above, ρ is the density, u is the velocity, p is the static pressure, ρg, and F are the gravitational body and external body forces, τ_{ij} is the stress tensor.

Turbulence is predicted using one of the following methods:

- Direct Numerical Simulation (DNS)
  - Currently, DNS is available for low Reynolds Number (Re) flows and is usually performed on simple geometries.
- Large Eddy Simulation (LES)
  - LES is recommended for certain classes of high Re flows with massive flow separation. Computationally, LES is still prohibitively expensive when used for solving external high Re numbers flows in a complex built environment, even with recently available computational power [11].
- Reynolds-Averaged Navier-Stokes (RANS) Equations
  - For most real-world building problems turbulence is, in principle, described by the Navier-Stokes equations [12], [13].

The RANS turbulence modeling is adopted in the current study to estimate wind velocity in terms of three directions, pressure profile, and turbulence parameters.

3 Methodology

Studies of wind comfort and wind safety involve combining statistical meteorological data with aerodynamic information and wind comfort and wind safety criteria. In this study, the criteria used in the evaluation of pedestrian-level winds surrounding the proposed development were based on the well-established "Lawson" criteria [14], [15] which couple the probability of exceeding winds at given statistical levels with wind speed magnitudes originally related to the Beaufort Land Scale, [16].

The proposed methodology for the quantitative wind modeling impact assessment is outlined below:

Step 1: Develop a localized weather database for the site:

- Surface wind data should be obtained from the nearest weather station which has a generally open exposure in all directions and hence is representative of all such areas in the region; and
- A local 10m height "reference" wind rose is then developed for the project site, by applying surface corrections to the representative regional wind data to take into account local terrain exposure factors by wind direction.

Step 2: Construct a discrete model for the site:

- An accurate 3D model for the proposed development is then created directly from computer CAD files.
- CFD simulations are then carried out within a domain that includes the buildings, terrain, and topography surrounding the project site.

Step 3: Predict wind speeds at areas of interest:

- The CFD model is used to predict the local wind conditions at all areas of interest, identifying locations of potential exceedance of the nominated wind criteria.
- The CFD simulations should cover all prevailing wind directions at the site.
- The assessment should consider seasonal variations in wind conditions (if relevant to the year-round usage of a specific area) and the type of pedestrian activity (sitting, standing, and walking).

Step 4: Determine wind probability incidence

- The CFD results are then combined with the statistics developed from the local wind rose to develop assessment predictions in terms of comfort and safety using the Lawson Criteria.

Step 5: Provide and test mitigations to satisfy the criteria

- Where wind speeds are found to be at undesirable wind levels, recommendations should then be made to reduce adverse wind impacts, e.g. using landscaping, porous windbreaks, canopies, etc.

  The proposed methodology will ensure that the assessed site including streetscapes and the proposed development will create a comfortable wind environment to live, work, and visit.

4 Case Study

The topic of the case study is pedestrian and balcony wind comfort and safety for a proposed development in London.

4.1 London Wind Climate

The data of interest in this London-based study are the annual return period mean hourly wind speeds and largest gusts experienced throughout the year, how these vary with azimuth, and the seasonal break-up of winds into the primary wind seasons.

- The Greater London Region experiences wind conditions typical of southeast England in general. It is affected by both Atlantic depressions and continental weather patterns, the latter occurring mainly in spring.
- When Atlantic depressions pass by the UK, the wind appears initially to come from the southwest quadrant and then the west to northwest as they move away. By the time northwest winds are occurring, such depressions have typically weakened.
- Moreover, northwest winds must also pass over more land and hence experience greater surface friction (and hence wind speed reduction).
- As a result, the southwest quadrant winds accompanying low-pressure weather systems are generally stronger than the associated northwest quadrant winds. Atlantic depressions are also often accompanied by clouds and rain.
- Continental weather patterns can produce cold spells in winter as well as hot, humid weather in summer. High-pressure systems that strengthen over Scandinavia produce a secondary, occasionally strong, prevailing wind in the Greater London area from the northeast.
- Finally, coastal areas in southern England experience onshore sea breezes from late spring through summer, which can reach London, originating from easterly quadrants.

Figure 1 shows annual wind roses at the nearest meteorological station (RAF Northolt) to the project site.

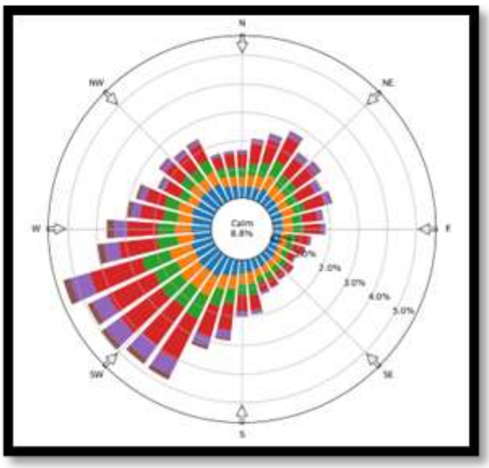

Fig. 1: RAF Northolt Meteorological Station Wind Rose

4.1.1 Wind Speed and Direction Statistical Model at the Project Site

The wind speed and direction probability distribution developed for the Project Site was determined as follows:

Step 1: Selection of Representative Regional Weather Station Site

- Surface Wind Data was obtained from the nearby RAF Northolt weather station.
- RAF Northolt has a generally open exposure in the immediate surrounds of the airport's anemometer and typical "semi-rural" or "suburban" type terrain further afield (houses, trees, woodlands, etc). It is, therefore, broadly representative of all such areas in the region and relevant to the proposed project site.

Step 2: "Reference" Regional" Wind Climate Model

- A local 10 m height, "Reference Regional" wind climate model was then developed by applying surface corrections to RAF Northolt weather data, using the locally assessed values for terrain category by wind direction.

Step 3: Local Project Site Wind Climate Model

- The final step was to adjust the Reference Regional wind climate model to the Project Site by applying surface correction factors reflective of the site's upstream terrain variations.

The Project Site local wind distribution derived as indicated above is shown in Figure 2 and Figure 3.

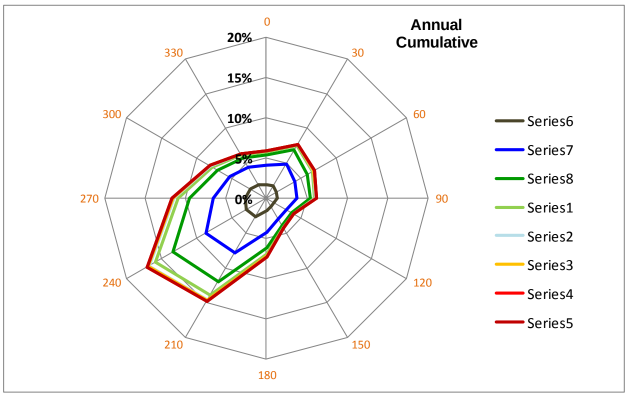

Fig. 2: Project Site Annual Cumulative Frequency

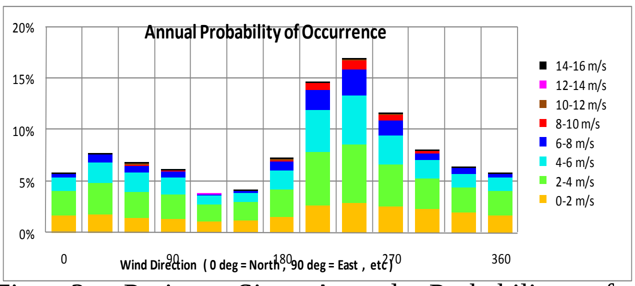

Fig. 3: Project Site Annual Probability of Occurrence

In the CFD Analysis, the local Project Site wind speed is used to normalize all predicted local wind speeds. As noted in **Section 3**, this is measured at a height of 10 m above ground level.

Mean winds with a once-per-year exceedance probability are shown in Figure 4 based on the adopted local Project Site wind model.

Stronger winds occurring on a once-per-year basis occur from the south to the west with a maximum from the west.

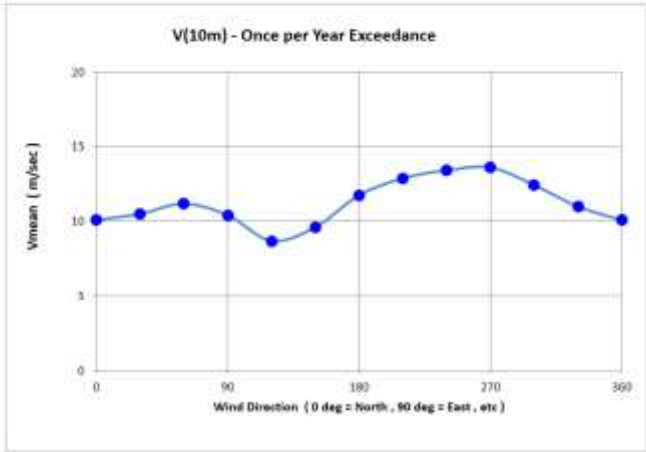

Fig. 4: Reference Height (10 m) Annual Recurrence Mean Wind Speed at Project Site

4.2 Criteria for Comfort and Safety

The criteria used in the evaluation of pedestrian-level winds surrounding the proposed development are based on the so-called Lawson criteria which couple the probability of exceeding winds at given statistical levels with wind speed magnitudes and associated impacts originally related to the Beaufort Wind Speed Land Scale, [16], refer to Table 1.

The Lawson criteria used in this study make use of the same wind speed ranges to address issues of interest in terms of both pedestrian comfort and safety.

These criteria, or rather guidelines, have been previously adopted by the London Docklands Development Commission (LDDC) and used for example on numerous building developments, eg within the Canary Wharf precinct. Indeed, they have been widely used for many years for ground-level wind assessments surrounding high-rise building developments right across the United Kingdom.

Table 1. Beaufort Wind Speed – Land Scale

Beaufort Force	Hourly Average Wind Speed (m/s)	Description of Wind	Noticeable Wind Effect
0	< 0.45	Calm	Smoke rises vertically
1	0.45 to 1.55	Light air	Direction shown by smoke drift
2	1.55 to 3.35	Light breeze	Wind felt on face; leaves rustle; wind vanes begin to move
3	3.35 to 5.0	Gentle breeze	Leaves, small twigs in constant motion; Light flags extended
4	5.6 to 8.25	Moderate breeze	Raises dust and loose paper; small branches move
5	8.25 to 10.95	Fresh breeze	Small trees, in leaf, sway
6	10.95 to 14.10	Strong breeze	Large branches begin to move; telephone wires whistle Umbrellas used with difficulty
7	14.1 to 17.2	Moderate Gale	Whole trees in motion Inconvenience felt when walking against the wind.
8	17.2 to 20.8	Gale	Twigs break off trees; personal progress impeded
9	20.8 to 24.35	Strong/Severe Gale	Slight structural damage (chimney pots, slates removed)
10	24.35 to 28.4	Storm	Trees uprooted; considerable structural damage
11	28.4 to 32.4	Violent Storm	Widespread damage – unusual event (in the UK)
12	> 32.4	Hurricane	Devastation – only occurs in the tropics

There are two distinct sets of wind criteria:

1) “Comfort” criteria relate a range of typical pedestrian activities such as purpose-walking, strolling, sitting, etc., to the local “Gust Equivalent Mean (GEM)” wind speed exceeding 5% of the time, on an annual return period basis, refer to Table 2.

Table 2. Lawson Wind Acceptability Criteria – Comfort Guidelines

Comfort Level	Beaufort Equivalent	“GEM” Wind Speed 5% Annual Exceedance	Description (see also Notes)
C5	1	2.5 m/sec	Dining
C4	2	4 m/sec	Sitting
C3	3	6 m/sec	Standing
C2	4	8 m/sec	Leisure Walking (Strolling)
C1	5	10 m/sec	Business Purpose Walking
CX	> 5	> 10 m/sec	Exceeds Comfort Criteria

- C4 is suitable for promenades, popular recreation areas with seating, reading newspapers, etc
-C3 is suitable for locations where pedestrians will likely be waiting for relatively short periods, eg at building entrances, pedestrian crossings, bus stops, etc
-C2 is suitable for activities such as window shopping
-C1 is suitable for footpaths used for purposeful pedestrian traffic only (eg not where shops might induce slower activities like window-shopping)
-CX suggests winds whose force can be felt by the body (branches on trees would be visibly swaying) and where walking will start to become inconvenient or challenging for certain classes of pedestrians, eg the frail, pedestrians holding parcels, parents holding children, etc.

2) “Safety” criteria cover instances when pedestrians might encounter difficulty in walking. They are defined by the incidence of “GEM” wind speeds occurring once or twice per year (probability exceedance level of 0.02%), ie during the most intense windstorm of the year, refer to Table 3.

Table 3. Lawson Wind Acceptability Criteria – Safety Guidelines

Safety Level	Beaufort Equivalent	“GEM” Wind Speed 0.2% Annual Exceedance	Description (see also Notes)
S2	6	15 m/sec	Non-Sensitive Usage
S1	7	20 m/sec	All-Weather / Sensitive Usage
SX	> 7	> 20 m/sec	Exceeds Safety Criteria

-S2 should be used to assess areas in constant usage, eg building entry points.
-S1 may be suitable for less frequently trafficked areas or areas that can be closed off in high wind conditions.
-SX suggests conditions where winds pose an actual hazard to pedestrians regardless of the activity.

In **Table 2** and **Table 3**, the GEM wind speed is taken as the maximum of the mean speed, and the gust speed is divided by 1.85.

In many urban locations, either because of exposure to open upstream conditions or because of street "canyon" effects, etc, the target Comfort and Safety criteria may already be currently exceeded. In such instances, a new development should ideally not exacerbate existing adverse wind conditions and, wherever feasible and reasonable, ameliorate such conditions.

Some latitude can be applied to the Comfort Criteria in particular, as the recommended limiting values were generally derived from subjective assessments of wind acceptability. Such assessments have been found to vary considerably with the height, strength, age, etc, of the pedestrian concerned.

4.3 Significance Criteria

The significance criteria used in the assessment of wind effects at measurement locations surrounding the site are based on comparing the predicted conditions at any particular location with the target usage at the same location (eg sitting, strolling, leisure walking, etc.) as defined by the Lawson Comfort Criteria.

- The proposed development is deemed to have a "Beneficial" impact at a particular location if wind conditions are calmer than the levels associated with the target usage at that location.
- The proposed development is deemed to have an "Unfavorable" impact at a particular location if wind conditions are higher than the levels associated with the target usage at that location.
- When wind conditions at a particular location, with the addition of the proposed development, are close to the levels associated with the target usage at that location, the impact is termed "Negligible"

The chosen significance criteria are shown in Table 4.

All "Unfavourable" impacts (whether minor, moderate, or major) are considered to be "significant", requiring mitigation for local conditions to become suitable for the intended use of the area.

Table 4. Significance Criteria Related to Lawson Acceptability Criteria

Impact	Expected Wind Microclimate
Beneficial – Major	Wind Conditions are 3-levels calmer than those desired.
Beneficial – Moderate	Wind Conditions are 2-levels calmer than those desired.
Beneficial – Minor	Wind Conditions are 1-level calmer than those desired.
Negligible	Wind Conditions are similar to those desired.
Unfavorable – Minor	Wind Conditions are 1-level windier than those desired.
Unfavorable – Moderate	Wind Conditions are 2-level windier than those desired.
Unfavorable – Major	Wind Conditions are 3-level windier than those desired or Wind Conditions are in the Lawson "CX" or "SX" category.

4.4 Modeling Configuration

To take into account the influence of the immediate surrounding environment, all neighboring buildings and local topography within a diameter of almost 1,000 m around the site were included in the developed CFD model. The model details are shown in Figure 5.

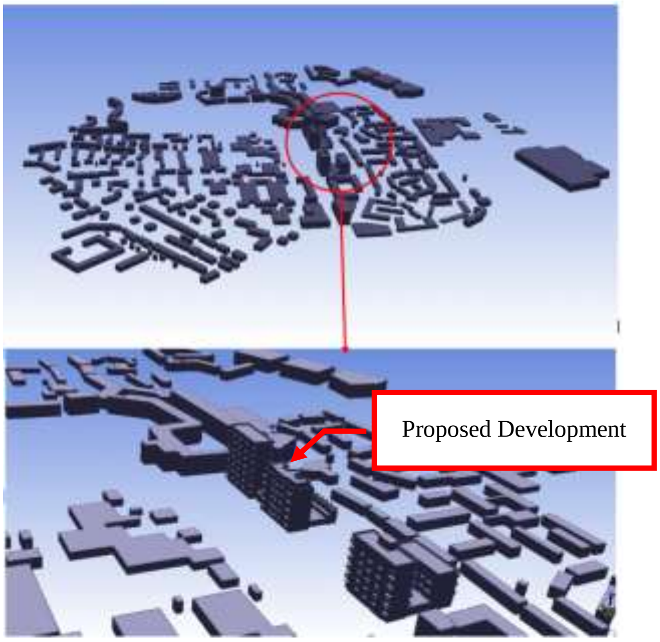

Fig. 5: 3D Model of the Proposed Development and Surrounds for CFD Model

4.4.1 Boundary Conditions

4.4.1.1 Wind Conditions

The wind speed probability distribution developed for the site was determined as follows:

- A local 10 m height "Reference" wind rose was developed based on a local climate model for the project site.
- Modeling was undertaken for twelve compass wind directions and public locations and communal roof terraces then checked for any exacerbation of the current wind conditions caused by the proposed development.
- At the upwind free boundary inlet, velocity profiles were derived from Met Bureau data and the UK EN 1991-1-4:2005+A12010 wind code.
- At the downwind and upper free boundaries "constant pressure" boundary conditions were applied.

4.4.1.2 Other Boundary Conditions
The following additional boundary conditions were used:

- Turbulence quantities (kinetic energy and dissipation rate) were calculated from empirical relationships.
- A wall function data group was used to avoid using a very fine mesh near the wall and improve turbulent flow simulation.

4.4.2 Discretisation
The software package utilized in the current CFD analysis is the commercially available code ANSYS-FLUENT, [17]. The CFD model solves continuity and momentum equations in the computational domain to predict the steady-state airflow inside and around the proposed development.

- A total number of 29,751,590 mixed elements was initially used to cover the computational domain. Based on a mesh sensitivity assessment, the mesh was then converted to polyhedral elements within ANSYS software. Polyhedral cells are especially beneficial for handling recirculating flows and are used to provide more accurate results than even hexahedra mesh. For a hexahedral cell, there are three optimal flow directions which lead to the maximum accuracy while for a polyhedron with 12 faces, there are six optimal directions which, together with the larger number of neighbors lead to a more accurate solution with a lower cell count, [11].
- A Realizable k-epsilon (rke) turbulence model was used [18] for all analyzed cases due to its ability to capture high gradient, airflow recirculation, and computational time advantage.
- A second-order numerical scheme was used for the discretization of pressure and momentum to obtain more accurate results.
- An iterative procedure was used to estimate the air velocity in terms of three directions, pressure profile, and turbulence parameters.

4.5 Area of Interest for CFD Modeling
With the CFD simulation, wind flow can be post-processed at any level. Representative public areas of interest, private terraces, and balconies are shown in Figure 6, Figure 7 and Figure 8.

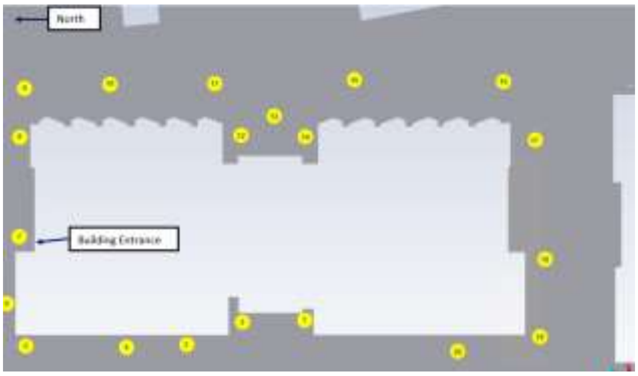

Fig. 6: Areas of Interest for a Selected Building – Ground Level

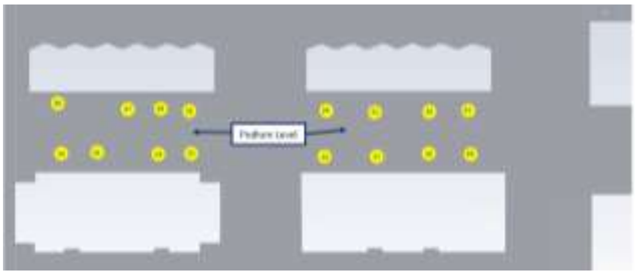

Fig. 7: Area of Interest for a Selected Building – Podium Level

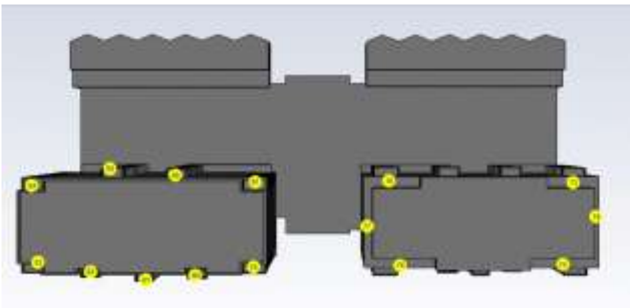

Fig. 8: Areas of Interest for a Selected Building – Upper-Level Terraces and Balconies

4.6 CFD Results and Discussions

4.6.1 Modeled Wind Directions
Twelve wind directions were modeled as part of the study, namely:

0°	North Winds	180°	South Winds
30°	Northeast Winds	210°	Southwest Winds
60°		240°	
90°	East Winds	270°	West Winds
120°	Southeast Winds	300°	Northwest Winds
150°		330°	

4.6.2 Sample Results and Discussion

Figure 9 shows the wind speed ratios ($V_{local}/V_{10m\ reference}$) on a colour-coded scale between 0 and 1.30. Dark blue represents still conditions at 0 m/s and red represents the highest wind speed. The following conclusions can be reached from Figure 9.

- The CFD model captures the fluid flow characteristics in significant detail. Wind approaches the site from the west at 270° as per the given boundary condition. Wind is then accelerated near the edges and stagnated and recirculated behind the buildings.
- There is a modest ground-level shielding from the upstream buildings to the west.
- The maximum velocity ratio on the ground level for this direction is 1.17.

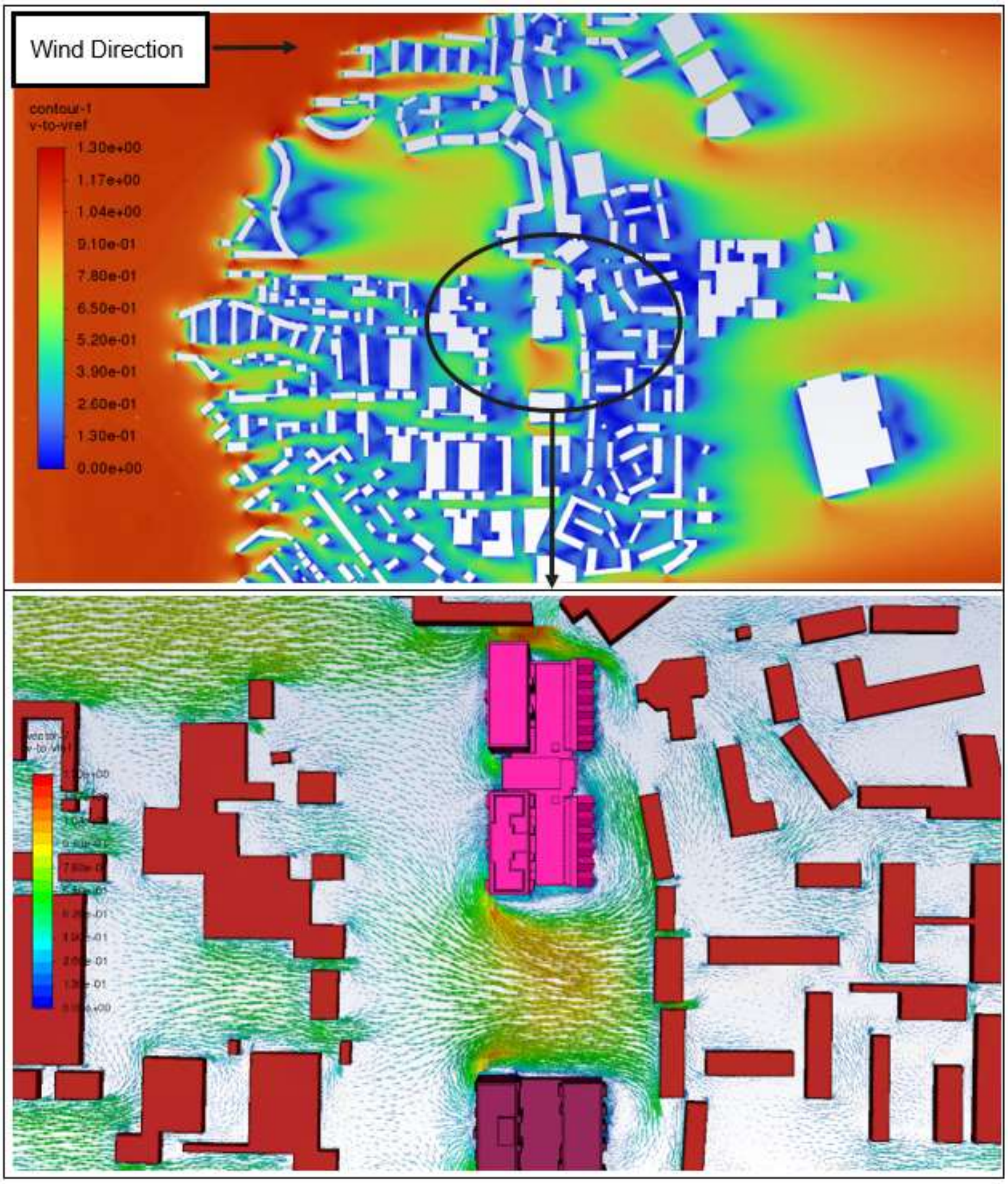

Fig. 9: Mean Velocities Ratios Coloured by Velocity Vector at 1.5 m above the Ground level

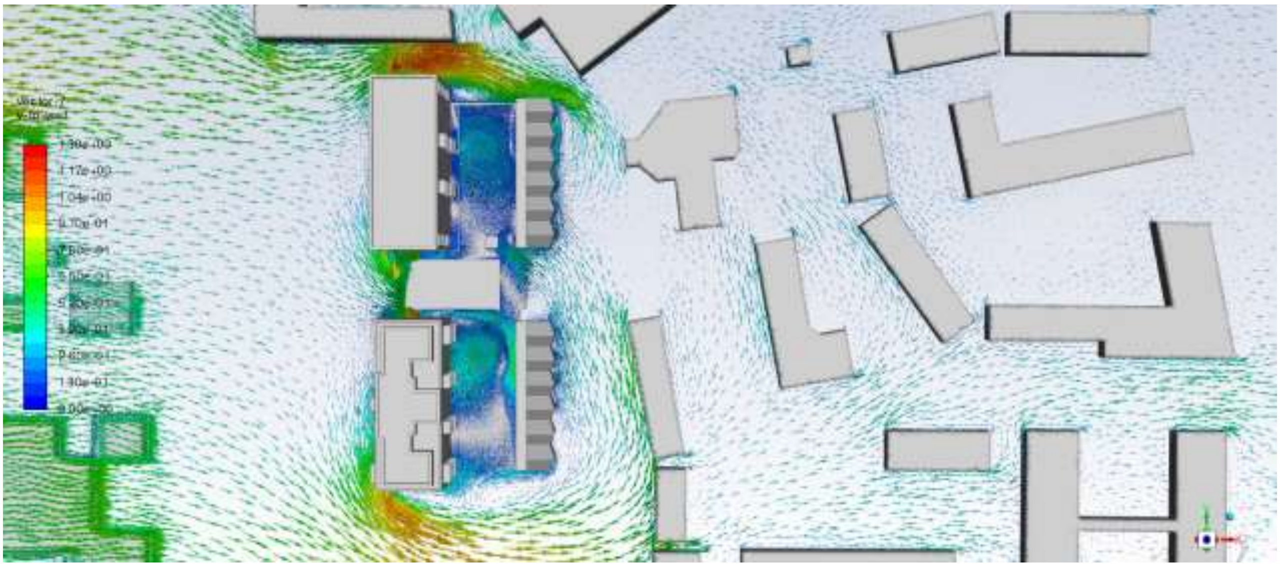

Fig. 10: Mean Velocities Ratios Coloured by Velocity Vector at 1.5 m above the Podium Level

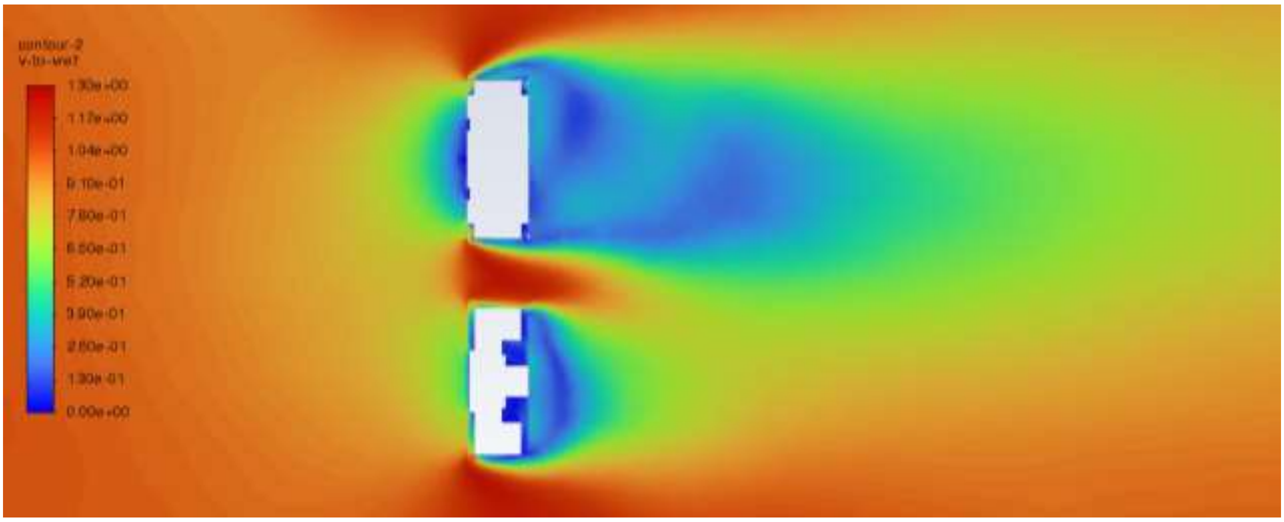

Fig. 11: Mean Velocities Ratios Coloured by Velocity Vector at the Balconies

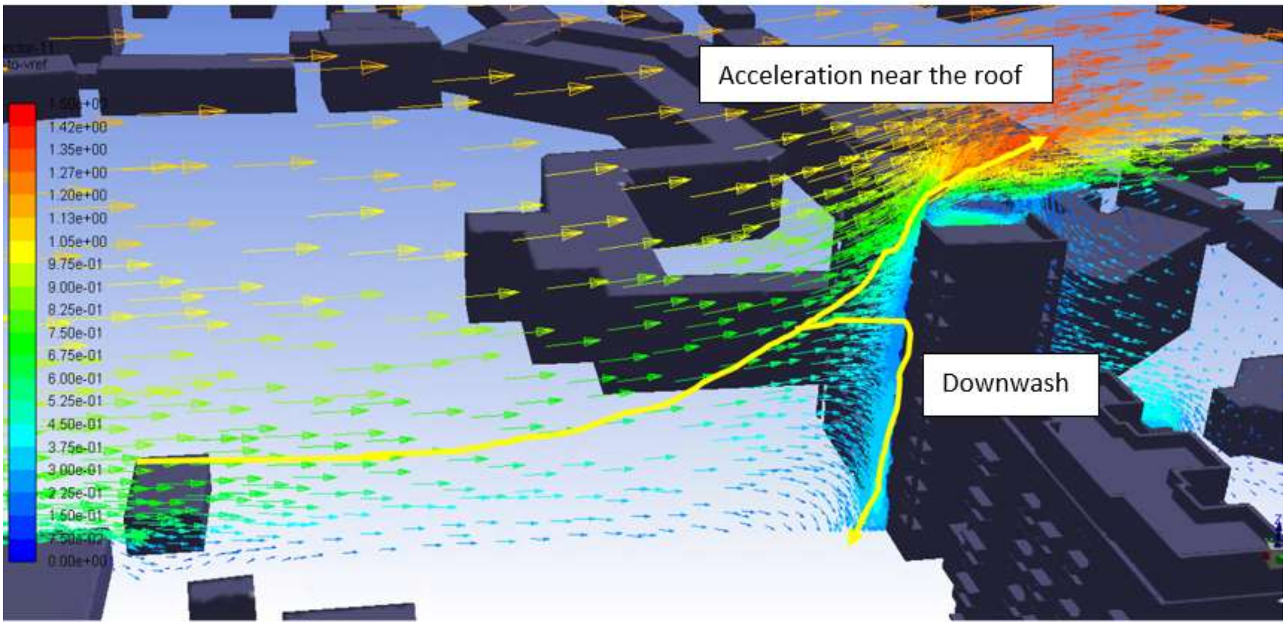

Fig. 12: Mean Velocities Ratios Coloured by Velocity Vector (2D vertical Section)

Table 5. Wind Speeds Ratios at the Region of Interest at Selected Locations – Future Scenario with Proposed Building

Location		0	30	60	90	120	150	180	210	240	270	300	330
Mean Wind Speed Ratio													
1	Ground Level	0.19	0.14	0.45	0.33	0.29	0.16	0.62	0.49	0.25	0.21	0.59	0.19
2	Ground Level	0.22	0.15	0.26	0.39	0.25	0.21	0.28	0.41	0.19	0.51	0.95	0.45
3	Ground Level	0.26	0.16	0.13	0.2	0.2	0.24	0.38	0.51	0.19	0.44	0.54	0.38
4	Ground Level	0.27	0.19	0.29	0.08	0.13	0.19	0.42	0.54	0.22	0.12	0.21	0.24
5	Ground Level	0.62	0.62	0.65	0.49	0.48	0.1	0.46	0.25	0.2	0.4	0.62	0.26
29	Podium Level	0.09	0.52	0.58	0.52	0.19	0.37	0.12	0.13	0.1	0.12	0.28	0.28
30	Podium Level	0.08	0.39	0.4	0.39	0.22	0.22	0.1	0.18	0.32	0.09	0.44	0.26
73	Balcony L10	0.56	0.85	0.99	1.17	0.86	0.84	0.79	0.45	0.26	0.09	0.12	0.29
83	Balcony L10	0.65	0.39	0.48	0.29	0.22	0.09	0.52	0.72	0.54	0.65	0.55	0.41
Gust Equivalent Mean (GEM) ratio													
1	Ground Level	0.22	0.16	0.51	0.38	0.33	0.19	0.69	0.55	0.29	0.24	0.65	0.22
2	Ground Level	0.25	0.17	0.30	0.44	0.29	0.24	0.32	0.46	0.22	0.57	1.01	0.51
3	Ground Level	0.30	0.19	0.15	0.23	0.23	0.28	0.43	0.57	0.22	0.50	0.60	0.43
4	Ground Level	0.31	0.22	0.33	0.09	0.15	0.22	0.47	0.60	0.25	0.14	0.24	0.28
5	Ground Level	0.69	0.69	0.72	0.55	0.54	0.12	0.52	0.29	0.23	0.45	0.69	0.30
29	Podium Level	0.11	0.58	0.64	0.58	0.22	0.42	0.14	0.15	0.12	0.14	0.32	0.32
30	Podium Level	0.09	0.44	0.45	0.44	0.25	0.25	0.12	0.21	0.37	0.11	0.50	0.30
73	Balcony L10	0.62	0.92	1.05	1.22	0.93	0.91	0.86	0.51	0.30	0.11	0.14	0.33
83	Balcony L10	0.72	0.44	0.54	0.33	0.25	0.11	0.58	0.79	0.60	0.72	0.61	0.46

Figure 10 and Figure 11 indicate the following:

- The development itself provides significant shielding to the podium area for westerly winds.
- Corner balconies experience modest wind speed acceleration from this direction.

The downwash impact of the building is shown in Figure 12. One can see that the downwash effect commences at around the two-thirds height level of the building and wind is deflected down toward the ground.

4.6.3 Wind Assessment Summary

Once the CFD results were analyzed for all wind directions, a summary of the local wind speeds, expressed as a ratio of the local ground level speed to the 10 m height reference wind speed, at each of the chosen representative locations, was prepared. Refer to Table 5.

4.6.4 Wind Assessment Results

The CFD results (refer to Section 4.6.1 and Section 4.6.2) were then combined with the wind probability information from the local wind rose (refer to Section 4.1.1) to develop assessment predictions in terms of Comfort and Safety using the Lawson Criteria (refer to Section 4.2).

The results have been computed on a probabilistic basis, enabling the calculation of wind events that will occur at the probability levels relevant to the Lawson Criteria, ie 5% and 0.02% exceedance levels on an annual basis, using the local site statistical wind data.

4.6.4.1 Lawson Safety Criteria Levels

Without any mitigation (eg landscaping) added to the development. The following conclusions can be reached from an analysis of the CFD results:

- No area will experience winds which may pose an actual hazard to pedestrians regardless of the activity.
- There are two ground-level locations (Location 6 and Location 19) predicted to experience wind speeds above the Lawson Safety Sa-2 criterion, refer to Figure 13. Wind mitigation is presented in Section 5.0.
- Lawson Safety Levels at all other locations remain at the “Sa2” level (suitable for all-weather use).

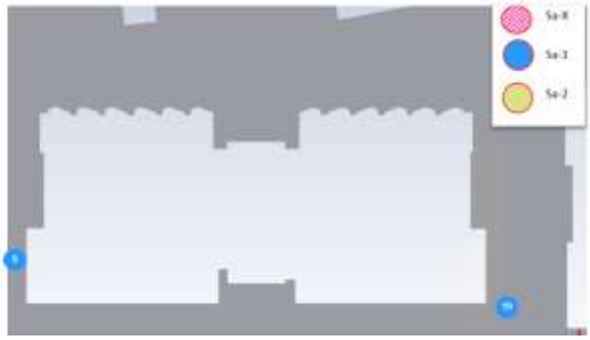

Fig. 13: Lawson Safety Criterion – Ground Floor

4.6.4.2 Lawson Comfort Criteria Levels

The Comfort Criteria assessment at selected locations is shown in Table 6. Note that these results are without any ground or podium-level mitigation (eg landscaping) added to the

Development. The following conclusions can be reached from the analysis:

Ground Level

- All areas are suitable for footpaths used for purposeful pedestrian traffic.
- The conditions at all locations range from C3 to C4, mainly due to the various low-level shielding elements.

Podium Level

- Some locations will experience a modest increase in wind speed, equivalent to one Lawson Comfort criterion level when compared to the target level criteria.
- All other areas are suitable for sitting.

Balconies and Terraces

- Some locations were shown to have the potential to experience increased wind speeds for selected wind angles above the “standing” comfort criteria or above the sitting criterion. For example, the condition at location 73 is C3.
- Other locations are suitable for standing and sitting.

Table 6. Assessment of Impacts of the Proposed Development for Selected Locations

Location	Predicted Comfort Level	Target Comfort Level	Impact
1	C4	Ground Footpath Ideal Target “C2” Leisure Walking	Beneficial – Moderate
2	C4		Beneficial – Moderate
3	C4		Beneficial – Moderate
4	C4		Beneficial – Moderate
5	C3		Beneficial – Minor
29	C4	Podium, Balconies and Terraces: Ideal target “C4” Sitting or “C5” Dining	Negligible
30	C4		Negligible
72	C4		Negligible
73	C3		Unbeneficial – Minor

5 Wind Mitigation

5.1 Strategy to Mitigate Adverse Wind Conditions

Strategies for ameliorating adverse wind conditions at the early and concept design stage should consider the following key parameters:

- Building orientation relative to prevailing wind directions.
- The proximity and shielding afforded by the adjacent buildings.
- Building height relative to adjacent buildings.
- Downwash winds deflected by the building towards ground level, which can significantly increase wind speed on the ground.
- Descending air flows accelerating around windward corners.
- Airflow through passageways, where the windward and leeward sides of the building are connected via lower-level openings or naturally ventilated corridors.
- Potential for wind speed-up due to venturi effect and airflow through narrow gaps.
- Potential for wind amplification in exposed corner balconies.

The following general strategies are recommended for mitigating adverse wind effects:

- Consider building setbacks to assist with breaking up the wind flow and redirecting it before it reaches the ground level.
- Podium levels are recommended for taller buildings to assist with deflecting downward wind before reaching the ground level.
- Provide canopies over the main building entrances.
- Place landscaping around the building to minimize downdrafts from impacting pedestrians.
- Place landscaping elements or architectural features near building corners to prevent pedestrian access and reduce winds and improve the wind environment for areas downstream of the corner.
- Place landscaping around the podium, rooftop terraces, and communal open spaces.
- Consider adding a canopy/awning or pergola over any designated seating areas impacted by downwash winds.
- Incorporate vertical windbreaks such as balustrades or a combination of plantings and screens or other practical wind shielding around the perimeter of exposed communal open space and/or roof gardens. These would ideally be at least 1.8m in height.
- Consider winter gardens or single-aspect balconies for exposed corner areas at higher building height where possible.

5.2 Site-specific Wind Mitigation

In light of the CFD simulation results, the wind modeling study led to the incorporation of the following wind mitigation treatments.

Ground Level

- Retention of the already planned ground-level landscaping; additional planting near the NW and SW corners (refer to Figure 14).

Podium Level

- Location of seating is positioned closer to windbreaks, e.g. adjacent to and underneath canopies of planting.

Balconies and Terraces

- CFD results at balconies were analyzed on both an annual and seasonal return period basis.
- The acceptable comfort conditions for balconies are considered to be that of Lawson “seating” (C4) or “standing” (C3) during summer months.
- Only 3 balconies were predicted to have conditions in exceedance of the standing comfort conditions. For this assessment the balconies were modeled as open (i.e. no screening), representing a worst-case scenario.
- Following the initial assessment, a workshop was held with the design team to discuss potential mitigation options. Following the workshop, it was determined that an impermeable balustrade up to a height of 1.1m with a maximum of 20% free area would be incorporated in the design to mitigate wind conditions to an acceptable comfort level for standing. Refer to Figure 15.

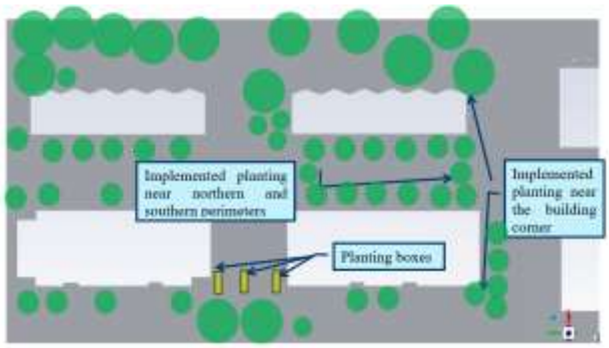

Fig. 14: Wind Mitigation – Ground & Podium Level

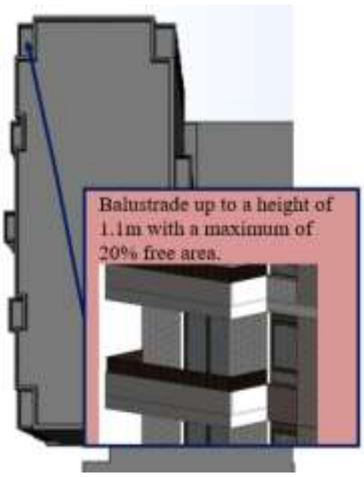

Fig.15: Example of Wind Mitigation – Selected Balcony

6 Significance of the Proposed Development Wind Impact

Following the adoption of the proposed mitigation options, the updated (“with mitigation”) CFD model predicted Lawson Comfort and Safety levels were again compared to the target levels for the areas of interest in Table 6.

The results at all locations were “Beneficial – Minor”.

7 Conclusion

This paper presents insights and key considerations for using Computation Fluid Dynamics (CFD) to simulate the Wind Microclimate in a Complex Urban Environment.

The current study involved developing a local 10m height, site-specific wind rose and then combining the statistical meteorological data with aerodynamic information and wind comfort and wind safety criteria. Where wind speeds were found to be at undesirable wind levels at areas of interest (ground level, podium level, terraces, balconies, etc), recommendations were made to reduce detrimental wind effects, e.g. using landscaping, porous windbreaks, canopies, etc.

The criteria used in the evaluation of pedestrian-level winds surrounding the proposed development are the well-established Lawson criteria which couple the probability of exceeding winds at given statistical levels with wind speed magnitudes originally related to the Beaufort Land Scale.

To take into account the influence of the immediate surrounding environment, all neighboring buildings, terrain, and local topography within a diameter of almost 1,000 m around the site were included in the developed CFD model. Furthermore, small canopies, all balconies, and semi-open spaces were modeled in detail are per the provided architectural drawings.

The CFD analysis offers a comprehensive range of output including velocity distribution, turbulence levels, etc, allowing the identification of hot spot areas that have unacceptable wind environments for further assessment and mitigation treatments to reduce wind speed to acceptable levels.

This paper provides a comprehensive approach toward the establishment of a robust CFD assessment of human comfort to ensure that proposed developments including streetscapes and buildings will create a comfortable wind environment to live and visit.

The current CFD study could be extended to examine air quality issues, wind-driven rain ingress, wind-generated noise issues and natural ventilation issues through the apartments.

References:

[1] NEN, 2006. *Wind Comfort and Wind Danger in the Built Environment*, NEN 8100, Dutch Standard, https://www.nen.nl/en/nen-8100-2006-nl-107592, 2006 .

[2] City of London Corporation, *Wind Microclimate Guidelines for the City of London*,https://www.cityoflondon.gov.uk/assets/Services-Environment/wind-microclimate-guidelines.pdf, 2019.

[3] Franke, J., Hirsch, C., Jensen, A., Krüs. H., Schatzmann, M., Westbury, P., Miles, S., Wisse, J. Wright, N., *Recommendations on the use of CFD in Wind Engineering*, International Conference on Urban Wind Engineering and Building Aerodynamics (Ed. van Beeck JPAJ), 2004.

[4] Frank, J., Hellsten, A., Schlunzen, H., and Carissimo, B., *Best Practice Guideline for the CFD Simulation of Flows in the Urban Environmen*t, Cost Action 732, 2007.

[5] Blocken, B.,Janssen, T. ,van Hoof, T., *CFD simulation for Pedestrian Wind Comfort and Wind Safety in Urban Areas - General Decision Framework and Case Study for the Eindhoven University Campus*, Environment Modelling Software Vol. 30, 2012, pp. 15-34.

[6] Blocken, B., Stathopoulos, T., & van Beeck, J., *Pedestrian-level wind conditions around buildings: review of wind-tunnel and CFD techniques and their accuracy for wind comfort assessment.* Building and Environment, Vol. 100, pp. 50-81, 2016

[7] Glanville, M. and Al-Khalidy, N., *Comparison of CFD prediction with wind tunnel and Full-scale Measurements for Bounded and Unbounded Wind Flow Scenarios*, 5th International Colloquium on Bluff Body Aerodynamics and Applications, Ottawa, Canada, 2004.

[8] Blocken, B., Stathopoulos, T., ASCE, F. and Carmeliet, J., *Wind Environmental Conditions in Passages between Two Long Narrow Perpendicular Buildings*, Journal of Aerospace Engineering, Vol. 21, Issue 4, 2008.

[9] Streichenberger, B., Chakir, R., Jouy, B., Waeytens, J., *Simulation and Validation of CFD turbulent airflow at pedestrian level using 3D ultrasonic anemometer in the controlled urban area "Sense-City",* Journal of Wind Engineering and Industrial Aerodynamics, Vol 219, 2021.

[10] Al-Khalidy N, City *Scale Pollutant Dispersion Modelling Utilising a Combination of Computational Fluid Dynamics and Standard Air Quality Simulation*, International Journal of Fluid Mechanics, Vol. 11, 2017, PP 210-217

[11] Al-Khalidy, N., Building Generated Wind Shear and Turbulence Prediction Utilising Computational Fluid Dynamics, WSEAS

Transactions on Fluid Mechanics, Vol.13, 2018, pp.126-135.

[12] B. Launder and D. Spalding, Lectures in Mathematical Models of Turbulence, Academic Press, London, England, 1972.

[13] Terence, T., *Finite time blowup for an averaged three-dimensional Navier–Stokes equation*. Journal of the American Mathematical Society, Vol. 29, 2016, pp. 601–674

[14] T. Lawson, T., and Penwarden, A., *The Effect of Wind on People in the Vicinity of Buildings*, Forth International Conference on Wind Effects on Buildings and Structures, Cambridge University Press, 1976, pp. 605-622.

[15] Lawson, T., *The wind content of the Built Environment,* Journal of Industrial Aerodynamics, Vol 3, 1978, pp. 93-105

[16] Royal Meteorological Society, Beaufort Scale, https://www.rmets.org/metmatters/beaufort-wind-scale, 2015.

[17] ANSYS, Ansys Fluent Theory Manual, USA 2024

[18] Menter, F., Sechner, R., Matyushenko, A., ANSYS, *Best Practice: RANS Turbulence Modeling in Ansys CFD*, https://www.ansys.com/resource-center/technical-paper/best-practice-rans-turbulence-modeling-in-ansys-cfd, Vol. 1, 2021.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed to the present research, at all stages from the formulation of the problem to the final findings and solution

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study. The original study was carried out to support a Development Application for the project site.

Conflict of Interest

The authors have no conflicts of interest to declare.