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Design for improving pedestrian wind comfort: a case study on a courtyard around a tall building

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ABSTRACT

Wind has an important impact on pedestrian comfort around buildings. Wind around tall buildings may cause significant problems at the pedestrian level and requires analysis. Wind comfort analyses are conducted via computational fluid dynamics (CFD) simulations and wind-tunnel studies. Engineering solutions are crucial in addressing wind discomfort issues. However, such solutions should not be applied independently of the architectural context. A multidisciplinary approach can bridge the gap between architectural design and engineering wind-comfort solutions. Adopting such an approach, this paper presents a design strategy to mitigate wind discomfort in a courtyard around a tall building. The CFD simulation results indicate that the proposed design provides the required wind comfort levels according to the NEN 8100 standard. In addition, using CFD simulations in combination with the standard is demonstrated to be an efficient method for improving pedestrian wind comfort. This outcome can help guide future research on wind comfort and thus contributes to improving the environmental quality of urban areas.

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Pedestrian wind comfort; building aerodynamics; wind comfort assessment; computational fluid dynamics (CFD)

Nomenclature

P	threshold exceedance probability (for all wind directions) (% time)
U	mean wind speed, m/s
$U_{\mathrm{ref,60\,m}}$	reference wind speed at a height of 60 m from the ground
U_{THR}	threshold wind speed at pedestrian level
k	turbulent kinetic energy, m^2/s^2
ε	dissipation rate of turbulent kinetic energy, m^2/s^3

1. Introduction

Tall buildings are commonly viewed as characteristic forms of urban settlements, and they provide a multitude of functions with a high number of floors on a small base area. Such buildings have important impacts on local wind characteristics in the near-field urban area. Because of the particular aerodynamic configurations generally associated with this building type, strong winds are usually accelerated at the pedestrian level in the adjacent urban environment. When the tall building has a simple rectangular shape, the boundary layer flow results in descending flows to the pedestrian level because of the pressure differences created by the velocity differences between the higher and lower levels of the building. Wind velocity increases with building height. Therefore, this down-flow is significant since the pressure is proportional to the square of the velocity (Bernoulli equation) (Stathopoulos and Blocken 2016). The down-flow may increase wind velocity and turbulent wind conditions. Today, many urban authorities only grant construction permission for a new tall building after a wind comfort analysis has indicated that the consequences for the pedestrian level wind area remain within acceptable limits (Blocken and Carmeliet 2008).

A more comfortable microclimate makes a building and/or urban area more sustainable since it tends to motivate pedestrians to walk, bike or use public transit instead of driving private motor vehicles (Wu and Kriksic 2012). It is commonly accepted that microclimatic conditions contribute to the quality of life in urban areas, both from the economic and the social viewpoint (Stathopoulos 2006). However, a thorough understanding of the wind comfort issues is required. To assess the wind comfort around buildings, experimental methods and numerical methods can be used.

The experimental method ensures reliable information related to airflow in and around buildings. However, the available data are generally limited because of the expense of experimental processes that require many sensor locations to obtain high-resolution data. Additionally, the approach is impractical for an architect trying to optimize building design. The experimental method may also extend the time spent on form optimization since it requires re-modelling the geometries and re-configuring the experimental setup. In addition, the parametric tools embedded in computational fluid dynamics (CFD) codes make it easy to investigate different geometrical forms or a principal form with different angles of attack. CFD overcomes certain limitations of wind-tunnel testing. As Blocken, Janssen, and van Hooff (2012) state, CFD does not have scaling problems and similarity constraints since simulations can be conducted at full scale.

In recent decades, various parametric studies related to the evaluation of the pedestrian-level wind environment around

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generic building configurations have been conducted. These studies have considered the effect of building height, shape and pattern of a group of buildings. In this section, several of these studies are summarized.

Stathopoulos and Wu (1995) investigated the effect of the spatial density of street blocks and the relative height of buildings. Zhang, Gao, and Zhang (2005) examined different building arrangements with different aspect ratios and plan area densities. Blocken, Charmeliet et al. (2007) assessed wind speed conditions in passages between parallel buildings with different passage width configurations. Li et al. (2015) evaluated the Venturi effect in passage ventilation between two non-parallel buildings. Allegrini and Lopez (2016) examined the influence of the angular configuration of two buildings on the local wind climate. Du et al. (2017) evaluated effects of lift-up design on pedestrian-level wind comfort in different building configurations for three wind directions. Xu et al. (2017) investigated pedestrian-level wind characteristics of super-tall buildings with various configurations.

As this review indicates, the literature on pedestrian wind comfort primarily focuses on the effect of dimensional parameters related to the design of generic building configurations on pedestrian-level flow. However, this paper proceeds beyond describing such typologies to propose a thorough wind-comfort analysis method that considers architectural and engineering perspectives. For this study, CFD assessment of the pedestrian wind-comfort conditions in the courtyard of a tall office building is described. In addition, measures to mitigate wind discomfort using specific architectural features and engineering solutions are proposed. First, the method to assess pedestrian wind comfort is described. Then, a brief case study on a building and its surrounding area is explained. Subsequently, the settings and parameters of the numerical simulations are briefly described. Last, the results of the wind comfort analyses and conclusions are provided.

2. Method for assessing wind comfort

Wind comfort assessment generally starts with climate data analysis. Therefore, a thorough understanding of the local climate based on a detailed analysis of long-term (at least 30 years) meteorological data is required (Wu and Kriksic 2012). After these data are analyzed, a correlation between the terrain roughness of the meteorological station site and the examined urban area is established. For this study, the aerodynamic circumstances of the site and the building are investigated. One important parameter of a location's aerodynamic characteristics is aerodynamic roughness length, which is the height above the displacement plane at which the mean wind becomes zero when extrapolating the logarithmic wind-speed profile downward through the surface layer. Although a degree of success has been achieved in relating this height to the arrangement, spacing, and physical height of individual roughness elements, such as trees or houses, aerodynamic roughness length is a theoretical height that must be determined from the wind-speed profile (American Meteorological Society 2018).

Meteorological stations are generally located in open areas with an aerodynamic roughness length of $y_0 = 0.003$ m. As such stations, wind speed is measured at 10 m height, and mean wind-speed values are observed on an hourly basis. To transfer these data to the investigated site, a logarithmic wind speed profile can be used since it provides the mean wind-speed distribution with height while taking aerodynamic roughness lengths into consideration. These data are used as the inlet boundary condition in CFD simulation to obtain wind-speed velocities at the pedestrian level, which is generally assumed to be 1.75 m.

The weather data and aerodynamic information are combined to assess the wind-comfort condition. At this point, the use of a comfort criterion is required. Several wind comfort criteria have been proposed. In Blocken, Janssen, and van Hooff (2012), four comfort criteria are compared. It is shown that different criteria may result in different conclusions regarding pedestrian wind comfort. The authors conclude that the criteria established by Lawson (1978) and Melbourne (1978) are the most restrictive, while the criteria established by Isyumov and Davenport (1975) are the most compatible with those of NEN 8100 (2006). Since there is no standard for wind comfort assessment, in this study, the NEN 8100 (2006) criterion was chosen since it represents the result of a long-term research project that evaluated the pros and cons of all existing criteria and creates a common framework for all climate types. NEN 8100 also enables the user to choose between wind-tunnel modelling and CFD to determine the design-related contribution to the building site as part of the transformation of wind statistics (Stathopoulos and Blocken 2016).

NEN 8100 adopts 5 m/s as a discomfort threshold for the hourly mean wind speed, and the local wind comfort is assessed based on the possibility that the wind velocity exceeds this value (Willemsen and Wisse 2007). The code identifies five classes of wind comfort, which are denoted with letters from A to E depending on the exceedance probability P of the threshold wind speed. These classes correspond to good, moderate or poor wind conditions (Table 1). It should be noted that there are different threshold values for different activities, e.g. sitting, strolling and traversing (Willemsen and Wisse 2007). To determine the exceedance probability in a practical case study, three steps are required (Blocken, Janssen, and van Hooff 2012):

(1) Obtain the wind speed ratios ($\gamma = U/U_{\mathrm{ref,60\,m}}$) as a design-related contribution from wind-tunnel experiments or CFD simulations. The reference wind speed value ($U_{\mathrm{ref,60\,m}}$) is the value of the inlet wind speed profile at a height of 60 m;
(2) Convert the threshold wind speed at the pedestrian level to a threshold wind speed at a height of 60 m ($U_{\mathrm{THR,60\,m}} = U_{\mathrm{THR}}/\gamma$);

Table 1. Probability values for wind speeds at the pedestrian level for wind comfort.

		Activity		
P (UTHR $>$ 5 m/s (in % hours per year)	Quality class	Traversing	Strolling	Sitting
$<$ 2.5	A	Good	Good	Good
2.5–5,0	B	Good	Good	Moderate
5,0–10	C	Good	Moderate	Poor
10–20	D	Moderate	Poor	Poor
$>$ 20	E	Poor	Poor	Poor

Source: Willemsen and Wisse (2007).

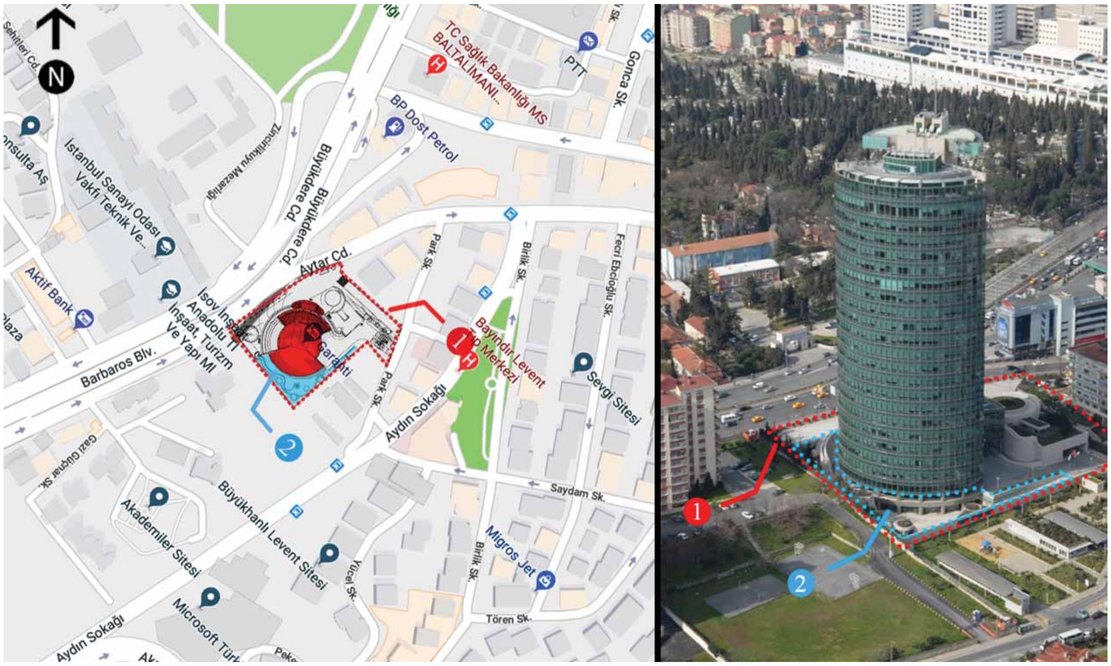

Figure 1. The case study object is a tall office building with a courtyard in the Zincirlikuyu-Maslak business district of Istanbul (1. Building site area; 2. Courtyard).

(3) Determine the percentage of time that the threshold value for the hourly mean wind speed at 60 m is exceeded according to the wind statistics of the location of interest. This 60 m height from the ground is determined based on the long-term experiments performed to prepare Dutch Practice Guideline NPR 6097.

Dutch Practice Guideline NPR 6097 only provides wind statistical data for the Netherlands. However, the wind statistics for the discomfort probability (i.e. the percentage of time that the discomfort threshold is exceeded) can also be obtained by using the Weibull distribution. The Weibull distribution function is a good approximation for the wind speed distribution (Formula 1). In the formula, b is the shape factor, u_c is the scale factor in m/s and $\bar{u}$ is the local annual average wind speed. The scale factor u_c is a measure for the characteristic wind speed of the distribution. It is proportional to the mean wind speed. The shape factor b specifies the shape of a Weibull distribution and assumes a value between 1 and 3. A small value of b signifies highly variable winds, while constant winds are characterized by a larger b. For the shape parameter $b = 2$, the following equations provide the Rayleigh distribution function used in this study (Formula 2).

$$f(u) = \frac{b}{u_c}\left(\frac{u}{u_c}\right)^{b-1} \exp\left(-\left(\frac{u}{u_c}\right)^{b}\right) \tag{1}$$

$$f(u) = \frac{\pi u}{2\bar{u}^2} \exp\left(-0.25\pi\left(\frac{u}{\bar{u}}\right)^{2}\right) \tag{2}$$

3. Description of the building and courtyard site

The case study site is located in the Zincirlikuyu-Maslak business district in Istanbul, where tall buildings are predominantly situated on land with an elevation of 123 m above sea level and open to the wind effects. The case study building is 122 m high and has 22 floors. Most other tall buildings are located far from the study building except a few mid-rise buildings to the building's north. The site plan of the building and an aerial photo are provided in Figure 1.

The aerodynamic roughness length of the terrain is predicted from the density and height of the surrounding building blocks. he prevailing wind direction is assumed to be NNE (Figure 2). The interpolation process is required by the NEN 8100 standard. An aerodynamic roughness length of $y_0 = 2$ m is adopted for the field near the site, which represents a large-town or city centre according to the updated Davenport Classification (Wieringa 1992).

The details of the surrounding terrain are examined to determine how the building form interacts with the wind. In this context, it is observed that the courtyard, in which a wind nuisance occurs, is located between the south and east side of the main building block. The courtyard has an organic form similar to the geometry of the building.

The courtyard is 11.45 m below the main entrance on the north side of the building and is connected to the staff cafeteria and service entrance. It is used continuously by the building occupants. The courtyard wall extends at an angle of approximately 8° from the floor and rises 5.3 m from the courtyard level (Figure 3). A partial horizontal glass porch is located in the courtyard of the service entrance. Apart from this porch, the upper part of the courtyard is completely open to the environment.

4. Numerical simulation settings

The turbulent flow within urban or industrial environments is generally modelled by the Navier-Stokes equations (Franke et al. 2011). Therefore, as an economical solution, steady-state 3D Reynolds-Averaged Navier-Stokes (RANS) equations are used. These equations are solved with the commercial CFD code FloEFD, which is commonly part of engineering fluid dynamics

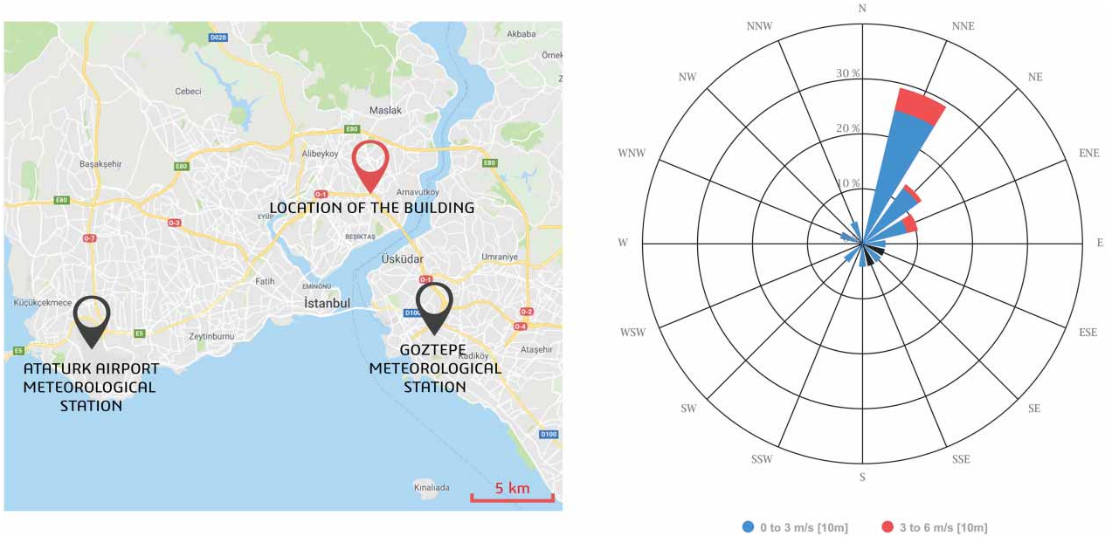

Figure 2. Wind rose of hourly mean wind speed for the location based on 30-year meteorological data (right) and the meteorological station locations (left).

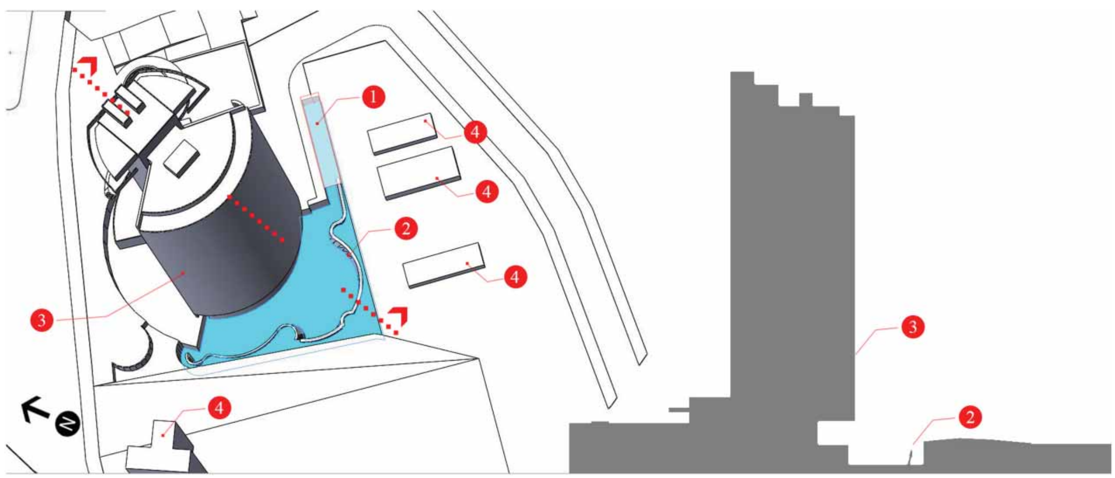

Figure 3. Case study building in perspective (left) and section (right) (1. Glass porch; 2. Courtyard wall; 3. Main building; 4. Neighbouring buildings).

software. The standard K-epsilon (k-ϵ) turbulence model with two-scale wall functions is used to provide closure. Two-scale wall functions are devised to fit a fluid's boundary layer profile relative to the main flow's properties:

(1) When the fluid mass centres of the near-wall mesh cells are located inside the boundary layer, the physical fluid flow boundary layer is thick.
(2) When the fluid mass centres of the near-wall mesh cells are located outside the boundary layer, the physical fluid flow boundary layer is thin.

These two approaches enable FloEFD to overcome the traditional CFD code restriction of having to employ a very fine mesh density near the walls in the calculation domain and to use immersed boundary Cartesian meshes for all geometries (Kalitzin and Iaccarino 2002).

CFD guidelines advise checking for the grid dependence of a solution. One should confirm that the prediction result does not change significantly with different grid systems. Best practices guidelines indicate that at least three systematically and substantially refined grids should be used so that the ratio of cells for two consecutive grids are at least 3.4 (Franke et al. 2011). The value of 3.4 means finer girds with 1.5 times the grid number in three dimensions. However, the CFD code of FloEFD does not require a conventional grid dependence check since it includes an algorithm to make the computational mesh finer in the necessary regions in which solid geometry and fluid field contacts and flow separation occur. This algorithm is applied when the simulation runs and a certain number of iterations occurs, and it continues to operate throughout the simulation until the solution appears.

The criteria for convergence represent another important parameter of numerical simulations. As indicated in the Architectural Institute of Japan (AIJ) CFD Guidelines, it is important to confirm that a solution does not change by monitoring the variables on specified points or by overlapping the contours among calculation results at different calculation steps (Tominaga et al. 2008).

A large computational model was created, and the computational domain, which consisted of nearly 8.4 million cells, was distributed in four distinct zones with respect to aerodynamic

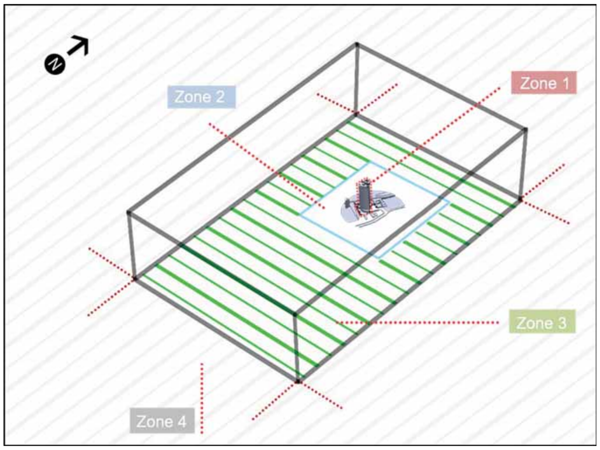

Figure 4. Computational domain with the zone arrangement.

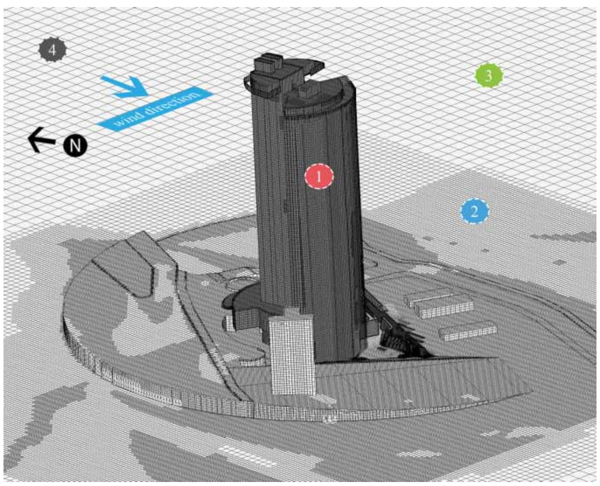

Figure 5. Mesh refinement levels of the zones.

roughness lengths. The nearby area around the site of interest is explicitly modelled (zone 2), and the far field containing tall buildings is implicitly modelled (zone 3) using an aerodynamic roughness length of $y_0 = 2$ m (Figure 4). While the entire domain area was 1400 m by 2600 m, the area with explicitly modelled buildings was 400 m by 400 m. An upstream domain extension of 5H and a downstream domain extension of 15H were left in the domain as advised in the guidelines (Franke et al. 2011). The site of interest in the centre of the computational domain is modelled in detail (zone 1) by using cells quietly smaller than the ones at the limits of the explicitly modelled region (Figure 5). A high-quality, high-resolution grid that consisted of only cut cells was developed to achieve fast convergence.

A neutral atmospheric boundary layer was represented at the inlet of the computational domain. For this study, a logarithmic mean wind speed profile was used with a reference wind speed of U_{10} of 3 m/s and an aerodynamic roughness length y_0 of 2.0 m to represent an upstream terrain (zone 4). When environmental pressure was applied at the inlet, zero static pressure was applied at the outlet of the domain. Therefore, the flow passed throughout the domain and developed completely. In addition, the sides and top of the domain were modelled with zero normal velocity and zero normal gradients of all variables. Thus, there was no

Figure 6. Wind speed ratios ($U/U_{\mathrm{ref},60\,\mathrm{m}}$) at the pedestrian level (1.75 m) under existing conditions.

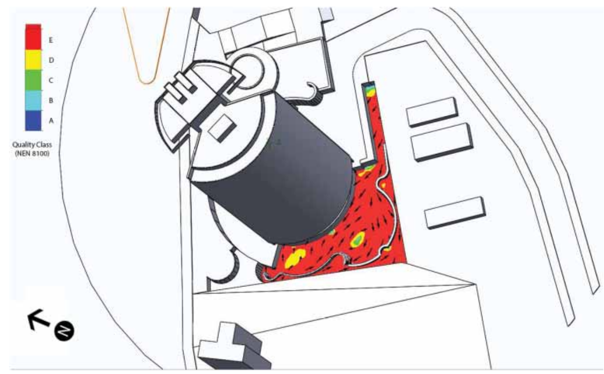

Figure 7. Wind comfort assessment at the pedestrian level (1.75 m) under existing conditions.

airflow friction at these borders of the domain. Lastly, at the walls of the solid surfaces, two-scale wall functions were used.

5. Wind comfort analysis of the existing conditions

Wind nuisance is experienced under the existing conditions of the courtyard by the building occupants. This area is primarily used for sitting and strolling activities. Before proposing a design, a detailed analysis of the current conditions was required. For this study, exceedance probabilities for wind nuisance and the related quality classes according to NEN 8100 were calculated. To determine the exceedance probability, wind speed ratios ($\gamma = U/U_{\mathrm{ref},60\,\mathrm{m}}$) as a design-related contribution were obtained from CFD simulations (Figure 6). Next, the threshold wind speed at the pedestrian level was converted to a threshold wind speed at a height of 60 m ($U_{\mathrm{THR},60\,\mathrm{m}} = U_{\mathrm{THR}}/\gamma$). Then, the percentage of time that the threshold value ($U_{\mathrm{THR},60\,\mathrm{m}}$) is exceeded was determined.

The NEN 8100 standard requires at least moderate conditions for sitting activities (i.e. quality class B or better). However, the wind comfort assessment reveals that the comfort levels largely remain in the E class (Figure 7). That is, the wind climate is poor for all typical activities (i.e. traversing, strolling and sitting) throughout the courtyard.

6. Design studies to mitigate wind discomfort

Generally, a building only induces high wind speeds at lower levels if a significant part of the structure is exposed to direct wind

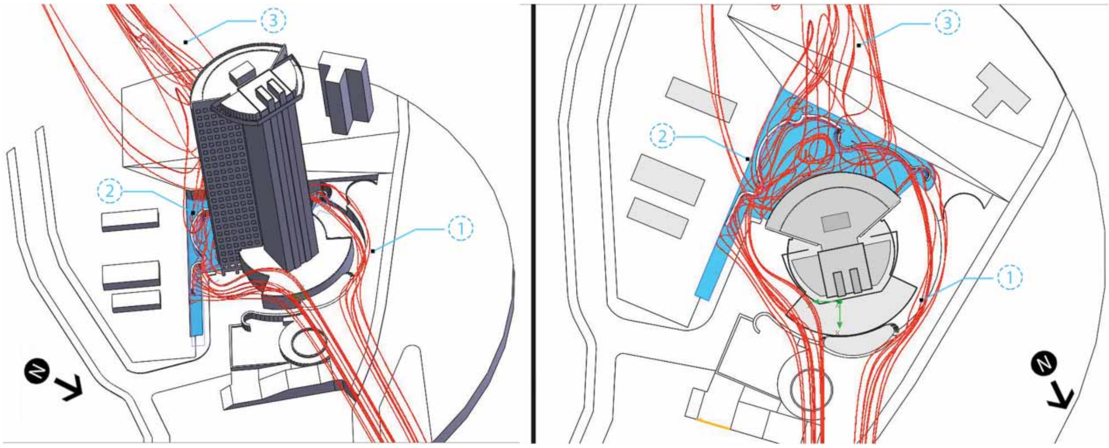

Figure 8. Flow streamlines in a perspective view (left) and a plan view (right) (1. Flow separation; 2. Interaction of the separated flows; 3. Recirculation of the flow).

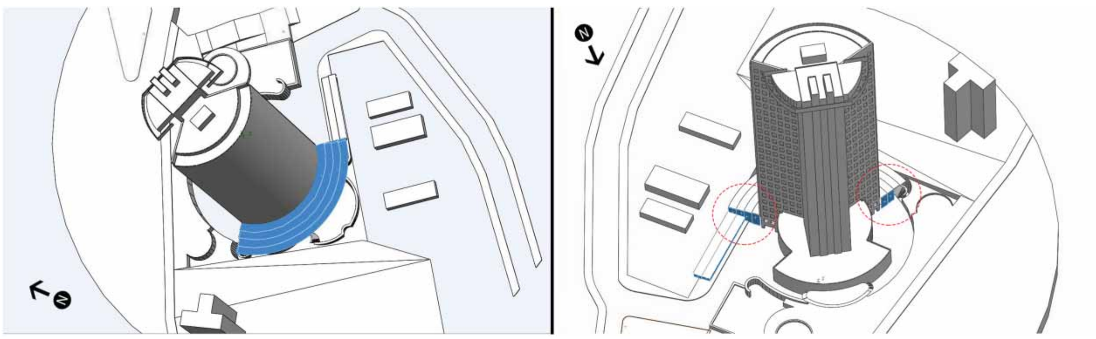

Figure 9. Details of the final design with the stepped canopy indicated in blue (left) and the vertical screens enclosed in red dashed lines (right).

flows. In fact, it is direct exposure to wind rather than building height alone that causes the problem (Stathopoulos and Blocken 2016). However, in this case, another type of pedestrian level wind is formed when high-speed winds pass from the windward side of the building to low-pressure regions on the leeward side (Figure 8). If we assume that a wind comes from the leeward (SSW) side of the building, the airflow will probably follow the building edges. This phenomenon occurs because cylindrical geometries provide a continuous path for the flow in contrast to rectangular forms. Stathopoulos and Blocken (2016) state that curved buildings generally promote lateral flow. Therefore, they behave better with respect to the effects of pedestrian-level winds. In most cases, this continuity of the building form results in a good wind climate. However, for the particular location examined in this study, the prevailing wind comes from the opposite side of the building, which is dominated by sharp corners.

The courtyard is located in a sub-level and has curved high walls that reflect the wind flow back. Since the airflow has no stable wake area as it continues on its path, turbulent areas with high wind speeds (higher than the $U_{THR} = 5\,\mathrm{m/s}$) occur. The main reason for the wind nuisance is channelling effects that occur on the both sides of the building at the courtyard level. These effects are particularly due to the corridor formed between the building corners and the courtyard sidewalls. When the streamlines are investigated in detail, it is observed that as a result of the channelling effect the airflow regime is unstable, and vortex flows are generated. It is clear that in this case the prevailing wind direction and the wind speed are the main variables. Three steps are observed in the process of vortex generation (Figure 8):

(1) The flow separates and accelerates along the building front edges.
(2) Wake-induced disturbances are observed due to the interaction between the separated flows coming from the building sides.
(3) A recirculation flow regime is created by the shear layer flow above the building.

The channel effect that occurs between the building corners and courtyard walls is obviously the main cause of the wind nuisance. To resolve this problem, one should consider that a continuous path of accelerated winds far from the courtyard level can interrupt this channel. Thus, a practical design option would be to attach a canopy to the leeward (SSW) side of the building.

Subsequently, a glass canopy attached to the building was investigated (Figure 9). However, it is observed that this measure only provides a horizontal path for airflow. Since the courtyard area that is covered is large, the canopy was separated into four sections horizontally and vertically. The area covered with the canopy was kept to a minimum to maximize the open area. Each canopy section is at a different level. However, the sections are connected to one another and the building. The stepped design of the canopy was expected to ensure the continuity of the flow. Additional vertical screens were placed at the outer edges of the canopy in the prevailing wind direction to prevent airflow to

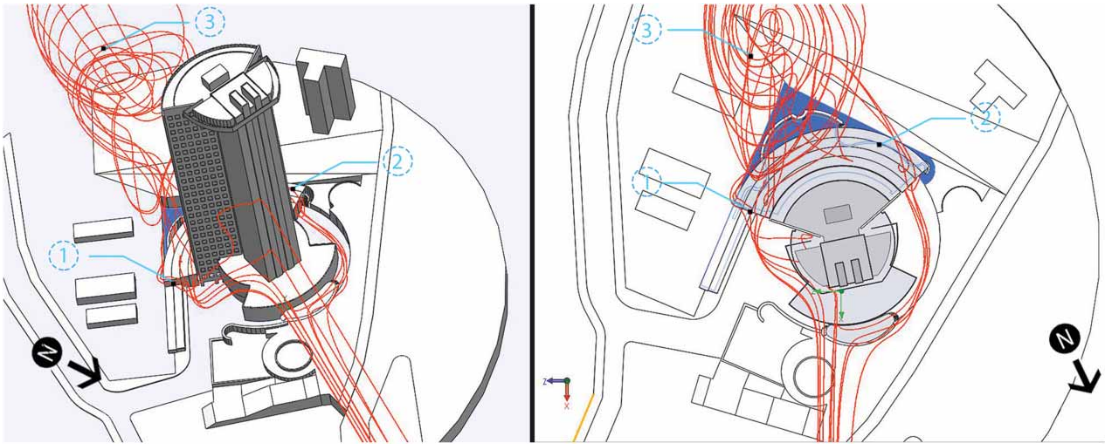

Figure 10. Flow streamlines in a perspective view (left) and a plan view (right) (1. Vertical screens; 2. Horizontal canopy; 3. Airflow transfer to distant open space).

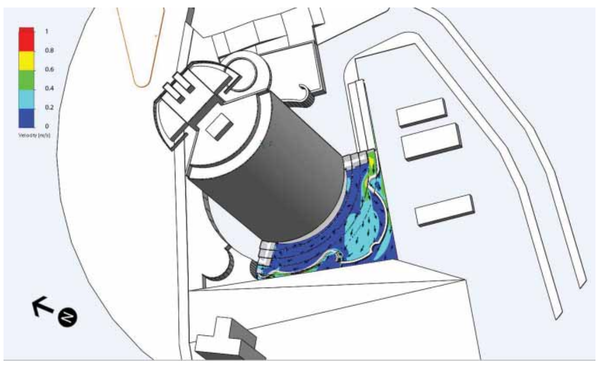

Figure 11. Wind speed ratios ($U/U_{\mathrm{ref,60\,m}}$) at the pedestrian level (1.75 m) of the final design.

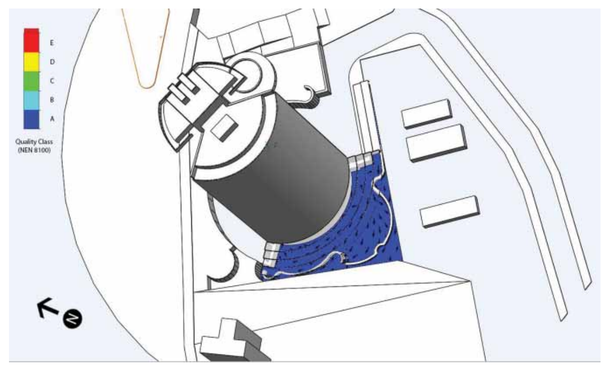

Figure 12. Results of a pedestrian wind comfort assessment at the pedestrian level (1.75 m) of the final design.

the courtyard (Figure 9). The effectiveness of the horizontal and vertical wind control elements analyzed in the CFD environment.

CFD simulation indicated that the pedestrian-level wind comfort was efficiently improved by the canopy and the vertical screens located on both sides of the building, which together overlap the entire area from the building to the external edges of the courtyard. The results of the CFD simulation reveal the following (Figure 10):

(1) With the help of the vertical screens, the airflow is directed over the canopy.
(2) Then, the horizontally stepped canopy smoothly transfers the flow over the courtyard.
(3) Finally, the vertical screens and the canopy create a short path between the high-pressure zone on the windward side of the building and the low-pressure zone on the leeward side that enables the airflow to be transferred to a relatively distant open area. Thus, the airflow is not directed to the east part of the building, where the neighbouring low-rise buildings are located.

With this solution, the wind quality in the walking area around the courtyard becomes class A (Figures 11 and 12) although quality class B was foreseen as an acceptable level for this area. The obtained wind comfort level is convenient for all activities according to the NEN 8100 standard. It should be noted that the neighbouring urban areas were taken into consideration when the wind discomfort was mitigated.

7. Conclusion

Tall buildings have important effects on the wind characteristics of the surrounding urban environment. Because of the specific aerodynamic forms commonly associated with such buildings, the airflow is usually accelerated at the pedestrian level, which results in a wind nuisance. Several studies have assessed pedestrian wind comfort around tall buildings. However, these studies generally analyse existing cases and describe specific cases of wind discomfort. In contrast, in this paper, a design method based on architectural and engineering perspectives is proposed. The method is then applied in a case study on a courtyard around a tall building in an urban area to evaluate the method's effectiveness in practice.

The studied building's form and location cause negative wind effects on the building's courtyard. A horizontal canopy with a stepped structure that does not completely cover the courtyard and is compatible with the building's architectural form was designed to reduce these effects. In addition, vertical wind control elements were designed to block the entrance of the airflow to the courtyard from the prevailing wind direction through the junctions of the building corners with the courtyard walls. The CFD simulation results indicated that the proposed design achieves the required wind comfort levels as defined in the NEN 8100 standard.

This research also demonstrates that using CFD simulations in combination with NEN 8100 (a wind nuisance standard) is an efficient method for improving pedestrian wind comfort. This outcome is significant because the method and the results described in this paper can serve to guide future research on wind comfort using CFD analysis. Thus, this study contributes to the improvement of wind quality in urban areas.

Research on wind comfort has primarily been conducted by wind engineers. Wind comfort studies have demonstrated the importance of solutions developed by such engineers. Advanced analysis methods that use CFD simulations can provide important aerodynamic information on a building and its surrounding area. However, design solutions based on such data should not be proposed without considering the architectural context. Even a simple attachment can change a building's form. Thus, cooperation with architects is significant when seeking to improve the wind quality of an urban environment. An interdisciplinary approach may be able to bridge the gap between wind-engineering solutions and architectural design processes. In a collective research project, the effect of several factors may be assessed. Thus, this approach can enhance the contribution of a building's physical parameters, which can be utilized to improve the urban areas around tall buildings.

Disclosure statement

No potential conflict of interest was reported by the authors.

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