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# USE OF CFD SIMULATIONS TO IMPROVE THE PEDESTRIAN WIND COMFORT AROUND A HIGH-RISE BUILDING IN A COMPLEX URBAN AREA

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## ABSTRACT

Wind comfort around a high-rise building in a complex urban environment is studied by combining Computational Fluid Dynamics (CFD) with the Dutch wind nuisance standard NEN 8100. The CFD simulations are performed with the 3D steady Reynolds-averaged Navier-Stokes (RANS) equations and the realizable k-ε model. Simulations are conducted according to best practice guidelines in CFD and are compared with on-site measurements at three street positions. The study shows that the high-rise building is the main cause of the wind nuisance at its base, as it catches the oncoming wind and deviates it to pedestrian level. Therefore, as a remedial measure, different sizes of canopies attached to the tower on both the south-southwest and the east-southeast side are studied.

## INTRODUCTION

As high-rise buildings become increasingly popular in urban city centers, wind nuisance becomes a more pronounced problem. Often high-rise buildings are built near pedestrian walking areas without taking the necessary precautions against high wind velocities at pedestrian level. This high-rise environment makes a stroll through the city certainly less comfortable compared to the situation without high-rise buildings. Moreover, sudden high-velocity wind gusts can cause people to lose their balance with possible severe consequences (Hunt et al., 1976).

Wind comfort and wind danger studies are performed preferably in the design phase of a new building but can also be performed afterwards, for situations with perceived wind nuisance. To assess wind comfort at pedestrian level, an appropriate wind comfort criterion and wind statistics can be combined with aerodynamic information from wind tunnel measurements or Computational Fluid Dynamics (CFD) simulations. Different wind comfort criteria exist, and extensive comparisons of different criteria were made by Bottema (2000) and Koss (2006). In a recent study by Janssen et al. (2013), four wind comfort criteria (Melbourne, 1978; Isyumov and Davenport, 1975; Lawson, 1978, NEN 2006) were compared using whole-flow field data for a complex urban area. This study showed that the differences in wind comfort assessment between the four criteria can be very large, stressing the importance of standardization of the wind comfort assessment procedure, in particular concerning the comfort criterion (Janssen et al., 2013).

Since 2006, the Netherlands has a wind nuisance standard (NEN 8100), which recommends wind comfort studies to be performed for new buildings with a height of 30 m or more. However, this is not mandatory, and high-rise buildings are sometimes still being built without a proper study of their consequences for the local wind climate. On the other hand, urban authorities have become more and more aware of the wind nuisance problems in their cities and might only grant a permit for new buildings after a wind assessment study has shown that the negative consequences of this new building for the wind environment remain limited.

Several studies have already been performed in which CFD simulations have been combined with the Dutch wind nuisance standard NEN 8100 (e.g. Blocken and Persoon, 2009; Blocken et al., 2012; Janssen et al. 2013). Like the current study, these studies are an answer to the call by Willemsen and Wisse (2007), co-developers of the standard, for research and demonstration projects with this standard.

These previous studies which applied the Dutch standard all focused on future situations where wind nuisance might occur. A unique aspect of the present study is that it considers an area where wind nuisance at pedestrian level is actually occurring and where it is evaluated as problematic and needs to be solved. The focus is a shopping street in the Dutch city of Eindhoven, which also contains restaurants and accompanying terraces. Shop and restaurant owners experience wind nuisance that might lead to lower sales. High wind speeds in this street cause people to walk past windows more quickly and to abandon the terraces because of the poor wind comfort.

The aim of this study is to analyze the causes of the wind nuisance and to evaluate remedial measures.

Since the study area is an existing situation, on-site measurements are performed to provide a first indication of the occurring wind conditions for different wind directions. In addition, these measurements are compared with the CFD simulations.

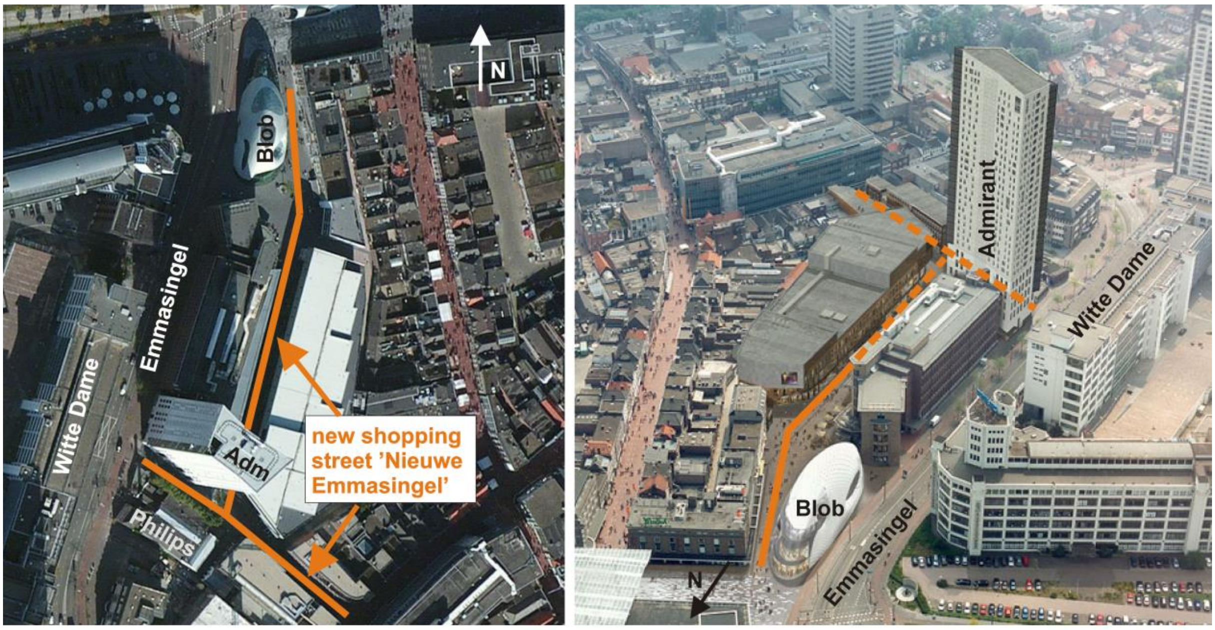


*Figure 1: Shopping street area with the Admirant Tower (Adm) and surrounding streets (orange lines)*

## CASE STUDY AREA

The case study area is a new shopping street called *Nieuwe Emmasingel* in the Dutch city of Eindhoven. This T-formed street contains medium-rise building blocks and a large tower of 105 m in height the Admirant Tower. Figure 1 gives an overview of the situation from different perspectives. The neighboring street *Emmasingel* which lies parallel to a part of the Nieuwe Emmasingel contains car, bicycle and pedestrian lanes. In comparison to the Nieuwe Emmasingel, the Emmasingel is not a strolling area.

## MEASUREMENTS

The measurements are performed with 3D ultrasonic anemometers at three different measurement positions in the shopping street (at 4 m height, Figure 2) plus a reference position at the nearby Eindhoven University campus during two summer months. The reference position is located on a meteorological tower on top of the Auditorium building at a height of 44.6 m, and the measured wind speed and wind direction at this position are denoted as $U_{ref,Aud}$ and $\varphi_{ref}$.

The measurement height in the street is 4 m instead of pedestrian height (1.75 m) for two reasons: (1) to avoid the influence of the presence of pedestrians on the measurements and (2) to reduce the risk of stolen or broken equipment.

The measurement frequency at all positions is at least 1 Hz, and measurement data are averaged over 10 minutes to provide values of mean wind speed and wind direction. Only data with $U_{ref,Aud} > 5$ m/s are retained, in an attempt to exclude measurement values affected by thermal effects. This is important because the CFD simulations that will be compared to these measurements will be performed for neutral atmospheric boundary layers and isothermal conditions (as required by the Dutch Standard NEN 8100).

Data sets of eight wind directions ($\varphi_{ref}$) were used for the comparison with the CFD simulations, these are 30°, 180°, 210°, 240°, 270°, 300°, 330° and 360° (degrees clockwise from North). For these wind directions, at least 10 measurement intervals could be used for the comparison, while for the other wind directions (e.g. 60°, 90°, 120° and 150°) less than 10 measurement intervals remained. Only data within the interval [$\varphi_{ref}$ - 5°; $\varphi_{ref}$ + 5°] were attributed to a given wind direction $\varphi_{ref}$. The measurement results will be presented together with the simulation results later in this paper.

*Figure 2: Measurement position A at the foot of the Admirant Tower*

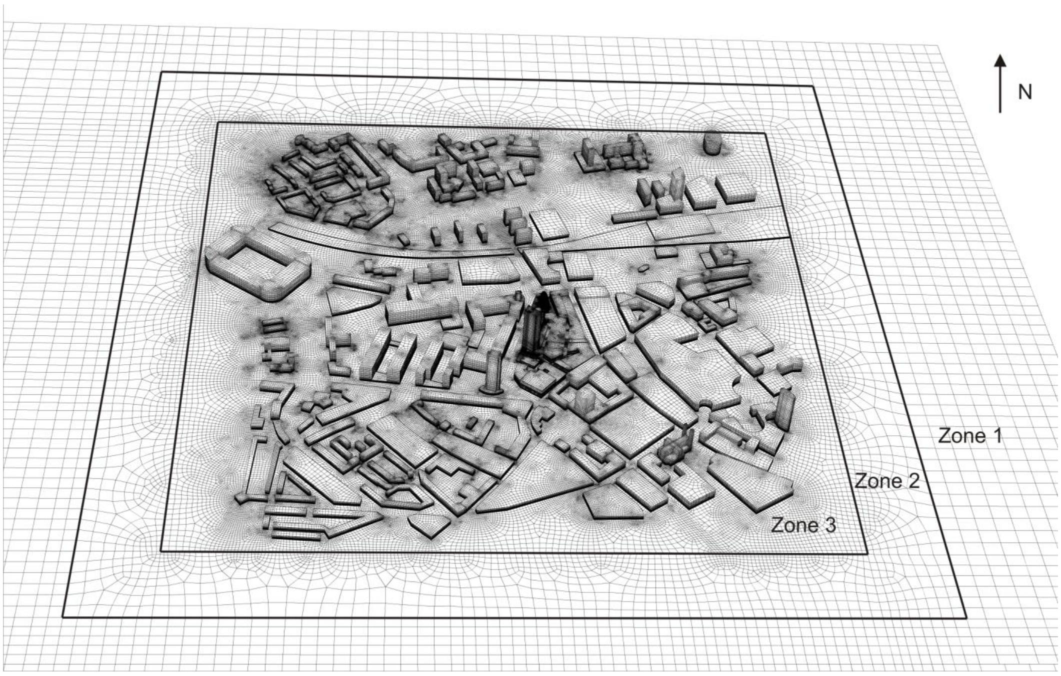


*Figure 3: Computational grid divided in three zones with different ground roughness parameters*

## COMPUTATIONAL MODEL AND PARAMETERS

### Computational domain and grid

The computational geometry and computational domain are constructed in accordance with the best practice guidelines by Franke et al. (2007) and Tominaga et al. (2008). Buildings with a distance to the shopping street of about 6 to 10 times their own width or height are included in the model as well as low-rise buildings that do not fulfill this requirement but are located in between medium- or high-rise buildings and the shopping street. Around this area of interest, the domain consists of an upstream (5H) and a downstream area (15H) according to best practice guidelines, where H is taken as the height of the highest building near the border of the explicitly modeled domain. The total height of the domain is about 5 times the height of the highest building. The resulting computational domain has dimensions of L x W x H = 2974 x 2762 x 500 $m^3$. The central part of the domain with explicitly modeled buildings covers an area of L x W = 1274 x 1312 $m^2$ (zone 3, Figure 3).

The computational grid consists of approximately 14.5 million cells and is created using the surface-grid extrusion technique presented by van Hooff and Blocken (2010). Only hexahedral cells are used for optimum grid quality and convergence properties. In accordance with best practice guidelines, pedestrian height (1.75 m – at which the results will be evaluated) is located in the middle of the fourth cell from the ground.

Figure 3 presents a large part of the computational grid, while Figure 4 zooms in on the grid around the Admirant Tower.

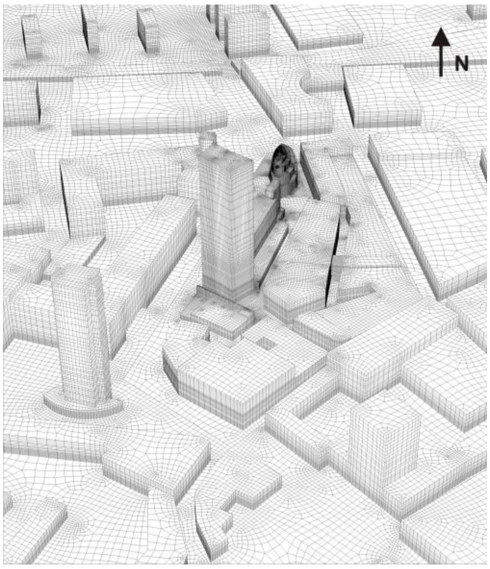


*Figure 4: Computational grid near the Admirant Tower.*

### Boundary conditions

Inlet profiles of mean wind speed U (m/s), turbulent kinetic energy k ($m^2/s^2$), and turbulence dissipation rate ε ($m^2/s^3$) are imposed at the inlet boundary of the domain. The mean wind speed profile (Eq. 1) is prescribed by the logarithmic law with an aerodynamic roughness length $z_0$ of 0.5 m or 1.0 m, depending on the upstream terrain roughness of the considered wind direction. A figure of the aerodynamic roughness lengths for the Eindhoven area can be found in Blocken et al. (2012). The reference wind speed ($U_{ref}$) is 5 m/s at 10 m high. Turbulent kinetic energy k and the turbulence dissipation rate ε are calculated according to Eq. (2) and (3).

$$U(z) = \frac{u^*_{ABL}}{\kappa} \cdot \ln\left(\frac{z + z_0}{z_0}\right) \quad (1)$$

$$k = 1.5(I_U U)^2 \quad (2)$$

$$\varepsilon = \frac{{u^*_{ABL}}^3}{\kappa(z + z_0)} \quad (3)$$

In these equations, $u^*_{ABL}$ is the friction velocity associated with the logarithmic wind speed profile and κ is the von Karman constant (0.42). For $z_0$ = 0.5 m, the inlet longitudinal turbulence intensity ($I_u$) ranges from 29% at pedestrian height (z = 1.75 m) to 5% at gradient height. For $z_0$ = 1.0 m, $I_u$ ranges from 39% (z = 1.75 m) to 8% at gradient height.

At the outlet, zero static pressure is specified. The sides and top of the domain are modeled as a slip wall (zero normal velocity and zero normal gradients of all variables). At the walls, the standard wall functions by Launder and Spalding (1974) are used, with the sand-grain roughness modification by Cebeci and Bradshaw (1977).

The ground "wall" of the domain is divided in three zones (see Figure 3) with different roughness parameters.

The first zone is the border area with a first cell height of 2.8 m. According to Blocken et al. (2007), the relationship between $z_0$ and the standard wall function roughness parameters $k_S$ (equivalent sand-grain roughness height) and $C_S$ (roughness constant) in the commercial CFD code ANSYS/Fluent is

$$k_S = \frac{9.793 \cdot z_0}{C_S} \quad (3)$$

$k_S$ has a maximum value of half the first cell height (=1.4 m), and $C_S$ can be set to 7 using a User Defined Function. Therefore, the aerodynamic roughness length of the border area can be set to $z_0$ = 1 m. Depending on the wind direction, the aerodynamic roughness length of this region is set to $z_0$ = 0.5 m or $z_0$ = 1.0 m. The second zone is a 200 m wide transition area between the border area and the area in which the buildings are modeled explicitly, i.e. with their actual dimensions. The first cell height is decreased to 1.4 m to gain a better transition to zone three. Therefore, the aerodynamic roughness has a value of 0.5 m in this zone. The third zone is the area of interest with explicitly modeled buildings. For the ground plane, the following roughness parameters are used: $k_S$ = 0.14 m and $C_S$ = 7. The first cell height in this zone is 0.5 m.

**Other computational parameters**

The CFD simulations are performed with the 3D steady Reynolds-averaged Navier-Stokes (RANS) equations and the realizable k-ε turbulence model (Shih et al., 1995). Pressure velocity coupling is taken care of by the SIMPLE algorithm. Pressure interpolation is second order. Second order discretization schemes are used for both the convection terms and viscous terms of the governing equations. The simulations were terminated when the scaled residuals did not show any further reduction with increasing number of iterations. The following minimum values were reached; z-velocity: $10^{-8}$, k, x- and y-velocity: $10^{-7}$, ε: $10^{-6}$ and continuity: $10^{-5}$.

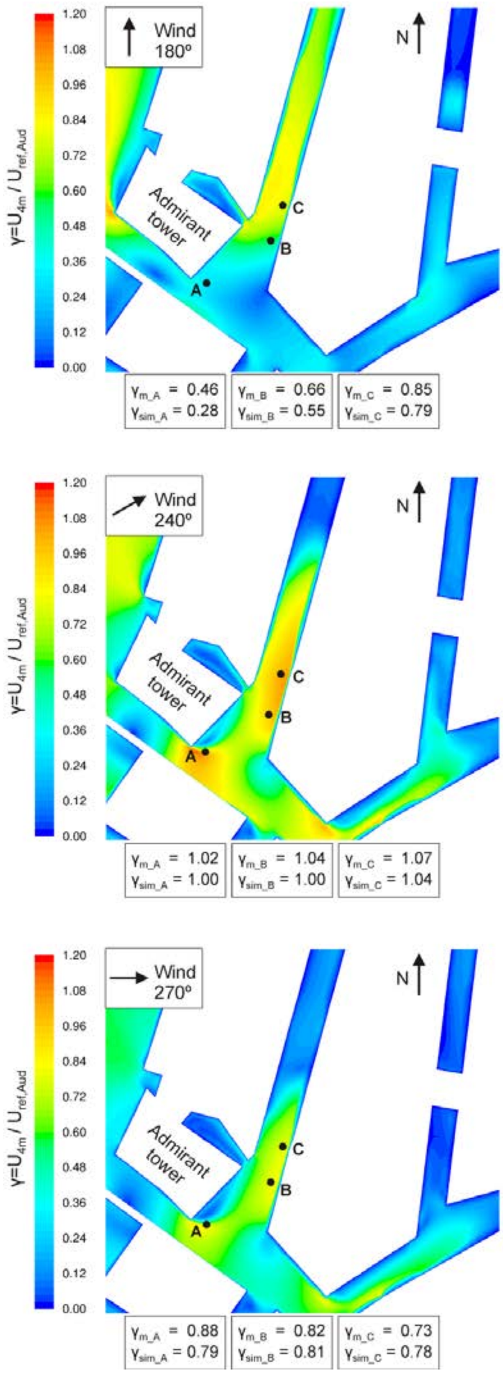


*Figure 5: Comparison of measured and simulated amplification factors γ for three prevailing wind directions. The contour plot shows the simulated amplification factors at 4 m height.*

## COMPARISON OF CFD SIMULATIONS WITH MEASUREMENTS

In this study, the measured and simulated wind speed amplification factors are compared with eachother. These amplification factors are defined as the ratio between the mean wind speed at the measurement position, and the mean wind speed at the reference position ($U_{mp}/U_{ref,Aud}$) for a given wind direction interval. Figure 5 shows the results for three important wind directions in the case study area (180°, 240° and 270°). For these three wind directions, an overall good agreement is obtained with an average absolute difference between measured and simulated amplification factors of 0.07. For all eight studied wind directions, the amplification factors show an average deviation of 0.15, which justifies the use of this computational model for the wind comfort study.

## WIND COMFORT ASSESSMENT

The pedestrian wind comfort in the shopping streets is assessed by determining the annual probability that the hourly threshold wind speed of 5 m/s is exceeded, as outlined in the Dutch wind nuisance standard NEN 8100. To determine the exceedance probability in a practical case study, three steps have to be taken for each of the 12 wind directions:

1) Obtain wind speed ratios ($\gamma = U/U_{ref,60m}$) from the CFD simulations. Note that these amplification factors differ from the amplification factors described in the section on comparing CFD simulations with measurements.
2) Convert threshold wind speed at pedestrian level to a threshold wind speed at a height of 60 m ($U_{THR,60m} = U_{THR}/\gamma$). In the Dutch standard, the safety criterion has a threshold of $U_{THR}$ = 15 m/s and the comfort criterion has $U_{THR}$ = 5 m/s.
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. In this study, the wind statistics for the twelve wind directions are provided by the Dutch Practice Guideline NPR 6097.

Depending on the exceedance probability, the wind climate is classified as good, moderate or poor for the activities sitting, strolling and walking fast (see Table 1). In a shopping street at least a moderate wind climate should be experienced for strolling (= wind class C).

*Table 1. Criteria for wind comfort according to NEN 8100 (2006a)*

| $P(U_{THR} > 5$ m/s) (in % hours per year) | Quality Class | Activity | | |
|---|---|---|---|---|
| | | 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 |

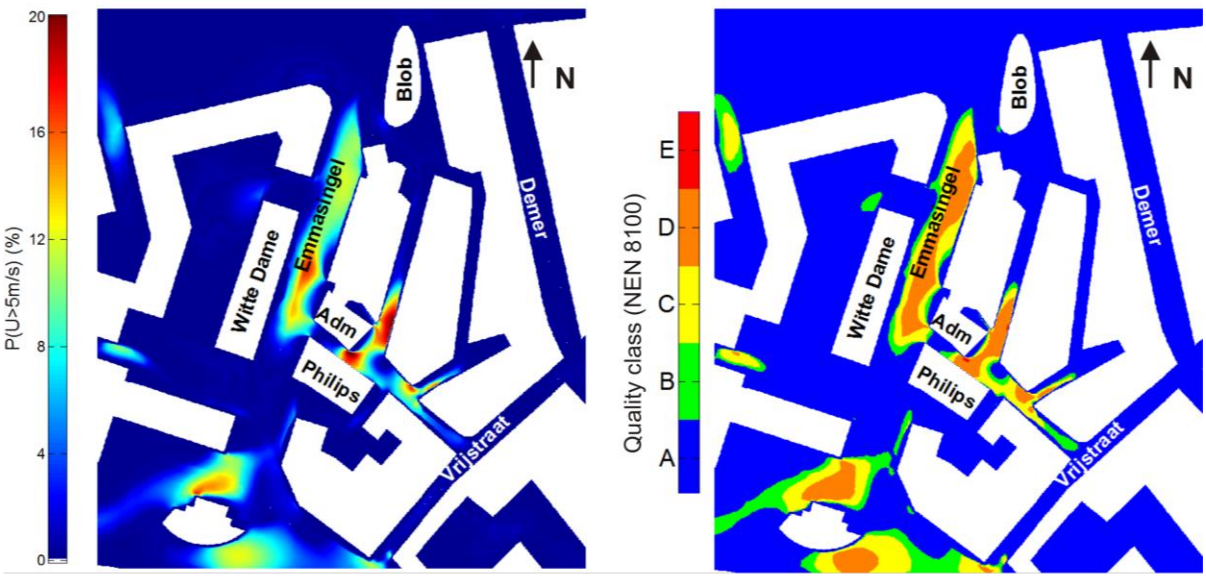


*Figure 6: Annual exceedance probabilities for wind nuisance and the accompanying quality class according to the Dutch standard NEN 8100*

## RESULTS

Figure 6 shows the wind comfort assessment for the current situation. On the left, it shows the annual exceedance probabilities for wind nuisance (P(U > 5 m/s), and on the right the quality classes according to NEN 8100 are given. On the southwest and eastside of the tower, a pedestrian walking area with wind quality class D (orange) exists, implying that this region has a poor wind climate for both strolling and sitting. The problems mainly occur for the prevailing southwest wind direction (240°), where also the highest wind speeds occur during the year. For this wind direction, air volume flow rates are analyzed to evaluate the contribution of both the Admirant Tower and surrounding buildings to the local wind climate in the shopping streets.

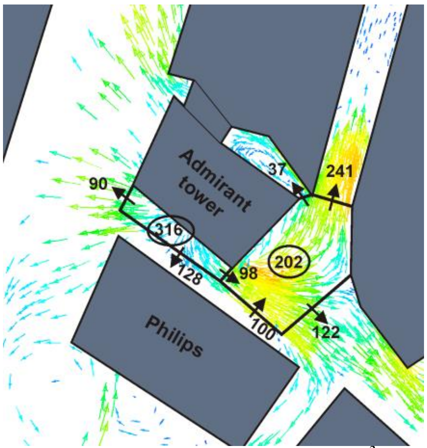


*Figure 7: Simulated volume flow rate($m^3/s$) at wind direction 240° around the Admirant Tower. Vertical circled volume flow rates at 4.5 m height and the horizontal volume flow rates through the streets are given*

Figure 7 shows the simulated air volume flow rates ($m^3/s$) in the current situation for a southwest wind. The circled values give the downstream air volume flow rate caused by the Admirant Tower. It can clearly be seen that all wind on street level at the foot of the Admirant is deviated down from the tower and is further directed through the adjacent streets. Because the Admirant Tower is the main cause of the wind nuisance problem, a possible solution would be to attach a canopy to the tower. Therefore, as a remedial measure, different sizes of canopies attached to the tower on both the south-southwest as the east-southeast side are studied.

Four different canopies ascending in size are shown in Figure 8 and 9. The figures also show the effect of these canopies to the exceedance probabilities of wind nuisance for wind direction 240°. Note that since the exceedance probability is shown for just one wind direction, the color scale in Figure 8 and 9 (0 – 7%) differs from the color scale in Figure 6 (0 – 20%). Simulations show that pedestrian wind comfort will be improved very effectively with an 11.4 m high canopy on both sides of the tower that overlaps the whole distance from the Admirant Tower to the buildings on the opposite sides of the shopping streets. The wind is directed over the canopy and onwards over building rooftops. In addition, the wind is not directed to the North part of the shopping street because the canopy provides a short-circuit between the overpressure zone on the windward side of the tower and the underpressure zone at the leeward side. This solution will bring the situation in accordance with the Standard NEN 8100 (see Figure 10). In the walking area around the Admirant Tower the wind quality classes range from A to C. Therefore, the wind climate is good to moderate for strolling as was intended with this study.

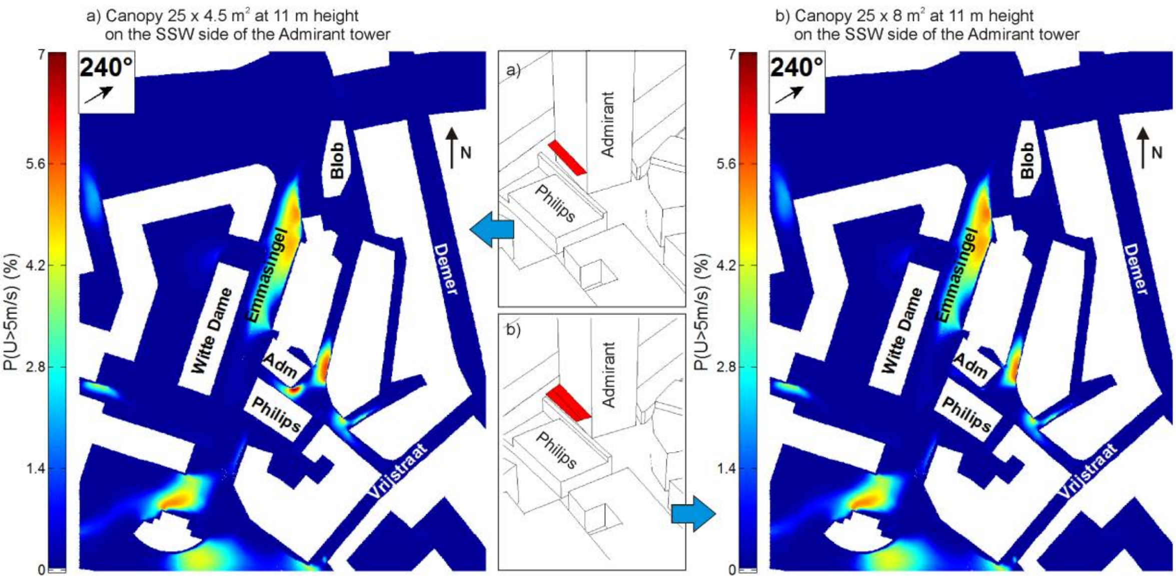


*Figure 8: Exceedance probabilities for two different canopies at the south-southwest facade of the Admirant Tower for a wind direction of 240°*

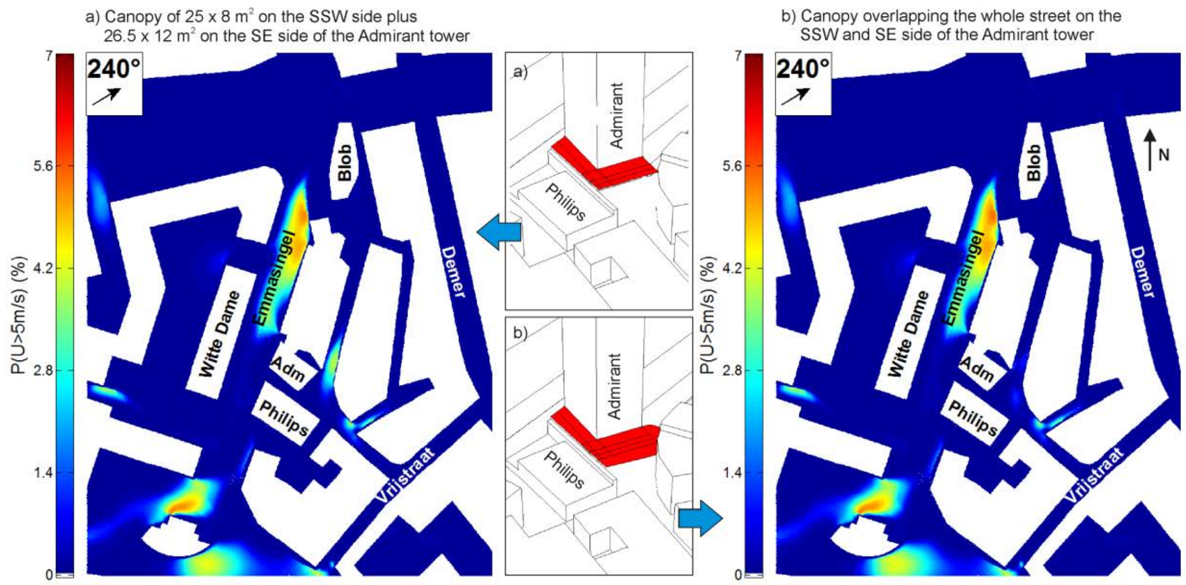


*Figure 9: Exceedance probabilities for two large canopies on both the south-southwest and southeast side of the Admirant Tower for a wind direction of 240°*

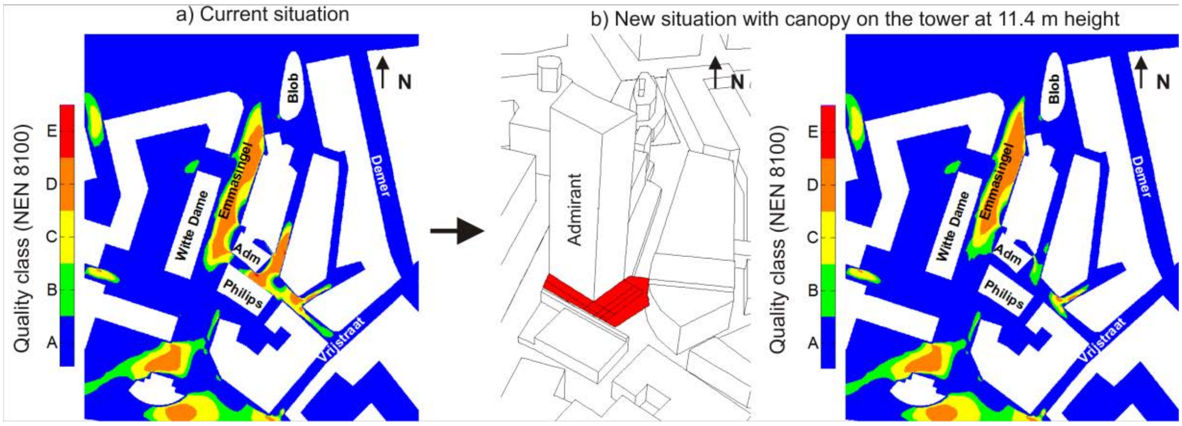


*Figure 10: Pedestrian wind comfort assessment around the Admirant Tower for the current and the new situation according to NEN 8100. Quality classes range from A (good) to E (poor).*

## DISCUSSION

It should be noted that this is a case study example and caution should be taken for generalization of the results. Wind flow around high-rise buildings in another complex urban area might behave differently. In addition, other urban areas will have different wind statistics to consider. Therefore, a canopy of similar size and height on a similar high-rise building could lead to a different wind climate and a new assessment of the local wind climate would be necessary.

## SUMMARY AND CONCLUSIONS

In this paper the Dutch wind nuisance standard NEN 8100 is applied on a case study area where wind nuisance is evaluated as problematic. The aim of this study is to analyze causes of wind nuisance in the selected case study area, and evaluate remedial measures. For this cause measurements and CFD simulations have been performed and compared to eachother. Measurements have been executed for two months with 3D anemometers at three different positions in the shopping street and a nearby reference position on a meteorological tower.

The computational geometry and computational domain are constructed in accordance with best practice guidelines. A high-quality and high-resolution computational grid is generated containing about 14.5 million hexahedral control volumes. The CFD simulations are performed for 12 wind directions with the 3D steady Reynolds-averaged Navier-Stokes (RANS) equations and the realizable k-ε model.

The CFD simulations show good agreement with the measurements, especially for the prevailing wind directions given in Figure 5 (180°, 240° and 270°). For these wind directions, the average absolute difference between measured and simulated amplification factors ($=U_{4m}/U_{ref,Aud}$) is 0.07. Simulations combined with local wind statistics show that the wind direction 240° contributes most to the annual wind nuisance at pedestrian level. The simulated volume flow rate (Figure 7) for this wind direction, demonstrates that all wind on street level at the foot of the Admirant is deviated down from the tower and is further directed through the adjacent streets. Because the Admirant Tower is the main cause of the wind nuisance problem, a possible solution would be to attach a canopy to the tower above the shopping street area. Different tower canopy sizes and orientations are studied. This resulted in the advice to create an 11.4 m high canopy on both sides of the tower that overlaps the whole distance from the Admirant Tower to the buildings on the opposite sides of the shopping streets. Simulations show that the wind is directed over the canopy and onwards over building rooftops. For southwest wind the canopy provides a short-circuit between the overpressure zone on the windward side of the tower and the underpressure zone at the leeward side. This measure will improve the wind climate at pedestrian level around the Admirant Tower leading to quality classes A to C according to NEN 8100. This implies that the wind climate is good to moderate for strolling as was intended with this study.

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