Jun 17th, 10:40 AM - 12:00 PM

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International Environmental Modelling and Software Society (iEMSs)
7th Intl. Congress on Env. Modelling and Software, San Diego, CA, USA,
Daniel P. Ames, Nigel W.T. Quinn and Andrea E. Rizzoli (Eds.)
http://www.iemss.org/society/index.php/iemss-2014-proceedings

Computational evaluation of pedestrian wind comfort and wind safety around a high-rise building in an urban area

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Abstract: Pedestrian wind comfort is analyzed for a new shopping street area in Eindhoven city center. Wind nuisance is especially perceived around a tower of 105 m high, at an intersection of two streets. The Dutch wind nuisance standard NEN 8100 combined with CFD (Computational Fluid Dynamics) simulations is used to assess the pedestrian wind comfort. Special care is given to the grid generation and comparison of the CFD simulations with on-site wind speed measurements. The effectiveness of a series of incremental remedial measures is analyzed. A large canopy is shown to be successful in bringing the wind comfort to an acceptable level.

Keywords*: Computational Fluid Dynamics (CFD); Wind flow; Built environment; Comfort; Validation.*

1 INTRODUCTION

In a new shopping street in the Dutch city of Eindhoven, which also contains restaurants and accompanying terraces, a large degree of wind nuisance is experienced. The aim of this study is to determine the contribution of a main tower building in this area and of surrounding streets to the pedestrian wind climate and to present a solution for the perceived wind nuisance. For this purpose a Computational Fluid Dynamics (CFD) model is created to determine wind speed amplification factors in the pedestrian area, which are combined with the local wind statistics and the Dutch wind nuisance standard NEN 8100 to assess the wind climate. To improve the wind climate in the shopping area the effectiveness of a variety of remedial measures in the vicinity of the tower is studied. Although the use of CFD for the study of pedestrian wind conditions in complex urban configurations is still an issue of debate, CFD has been employed on a few occasions in the past as part of wind comfort assessment studies (e.g. Richards et al. 2002, Blocken et al. 2012, Janssen et al. 2013). The Dutch standard itself specifically mentions that studies can be performed by either wind tunnel testing or CFD. The CFD simulations in this study are conducted according to the Best Practice Guidelines (e.g. Franke et al. 2007, Tominaga et al. 2008) and are compared with experimental data.

2 GEOMETRY AND CFD SIMULATIONS

Figure 1a shows the area of interest in this study, which is the Nieuwe Emmasingel, indicated with the orange lines. The Nieuwe Emmasingel consists of a rather long shopping street with mid-rise building blocks on the sides and an intersecting street at the foot of a high-rise building – the Admirant tower (105 m). Southwest of the Admirant Tower, another high-rise building is located, which is the 96 m high Regent Tower.

A large computational model containing all the high-rise buildings in the neighborhood was created, consisting of about 9.2 million cells. The area with explicitly modelled buildings was 1274 m by 1312 m and according to the Best Practice Guidelines (Franke et al., 2007, Tominaga et al. 2008) an upstream domain extension of 5H and a downstream domain extension of 15H were included in the domain. Figure 1b shows the grid with the area of interest in the center of the domain. The center part is modelled in more detail and contains smaller cells than the building blocks at the borders of the explicitly modelled area. Special care was given to the development of a high-quality and high-resolution grid that consists of only hexahedral cells to gain fast convergence even with the requested second order discretization schemes. The grid was constructed using the grid generation technique by van Hooff and Blocken (2010), which allows a large degree of control over the quality of the grid and its individual cells. At the inlet of the domain a logarithmic mean wind speed profile, representing a neutral atmospheric boundary layer, is imposed with an aerodynamic roughness length z_0 of 0.5 or 1.0 m depending on the wind direction, and a reference wind speed U_{10} of 5 m/s. The aerodynamic roughness length is determined based on the classification of terrain roughness by Davenport, updated by Wieringa (1992). Turbulent kinetic energy k is calculated from I_U using $k = 1.5(I_U U)^2$. 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. The turbulence dissipation rate $\varepsilon = u^{*3}/(\kappa(z + z_0))$, where z is the height coordinate, κ the von Karman constant (κ = 0.42) and u* the friction velocity. Zero static pressure is imposed at the outlet of the domain and the sides and top of the domain are modeled as slip walls (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 roughness is taken into account by modification of standard wall functions with appropriate values for the equivalent sand-grain roughness height k_S and the roughness constant C_S (Blocken et al., 2007). The 3D Reynolds-Averaged Navier-Stokes (RANS) equations are solved with the commercial CFD code Ansys Fluent 14 (Ansys Inc, 2009). The realizable k-ε model (Shih et al., 1995) is used to provide closure. This choice is based on earlier successful validation studies with this model (e.g. Blocken and Carmeliet 2008, Blocken et al. 2012). In addition, the use of this model will be validated further in this paper. Second-order discretization schemes are used for both the convective and viscous terms of the governing equations. The SIMPLE algorithm is used for pressure-velocity coupling and second order pressure interpolation is used.

3 ON-SITE WIND SPEED MEASUREMENTS

On-site measurements were performed with 3D ultrasonic anemometers during two summer months at three measurement positions in the shopping street (at 4 m height) plus a reference position at the nearby Eindhoven University campus (at 44.6 m height). 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 a mean wind speed at the reference position that exceeds 5 m/s is retained to exclude measurement values affected by thermal effects. In the CFD simulations these thermal effects are also not taken into account (as required by the Dutch Standard NEN 8100). Data sets of eight wind directions (φ_{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 [φ_{ref} - 5°; φ_{ref} + 5°] were attributed to a given wind direction φ_{ref}.

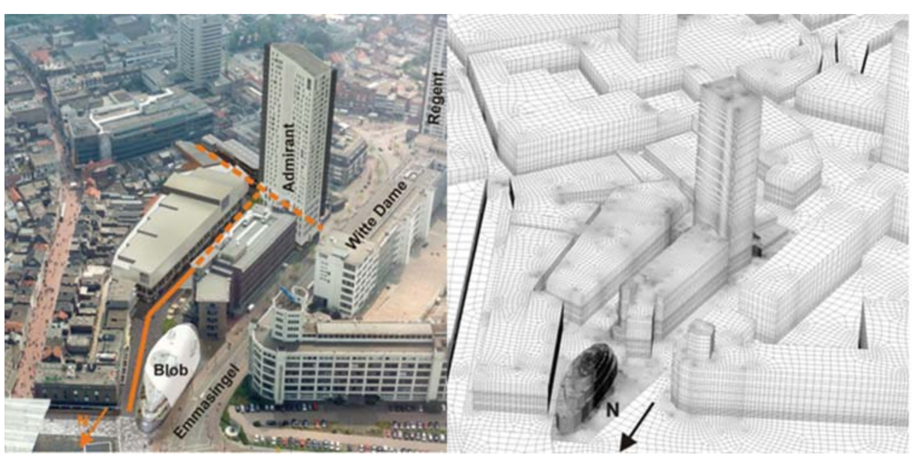

Figure 1. The area of interest in this study is the new shopping street Nieuwe Emmasingel (indicated in orange) in the city of Eindhoven.

4 COMPARISON OF CFD SIMULATIONS WITH ON-SITE MEASUREMENTS

A comparison is made between simulated and measured wind speed amplification factors $U_{mp}/U_{ref,Aud}$, where U_{mp} is the wind speed at one of the measurement locations and $U_{ref,Aud}$ is the wind speed at the reference location. Results for two of the eight selected wind directions are shown in Figure 2. For these two prevailing wind directions (240° and 270° degrees from north) the average difference between measured and simulated amplification factors is 0.04. For all eight studied wind directions, the amplification factors show an average deviation of 0.15, which is considered a good agreement and which justifies the use of this computational model for the wind comfort study.

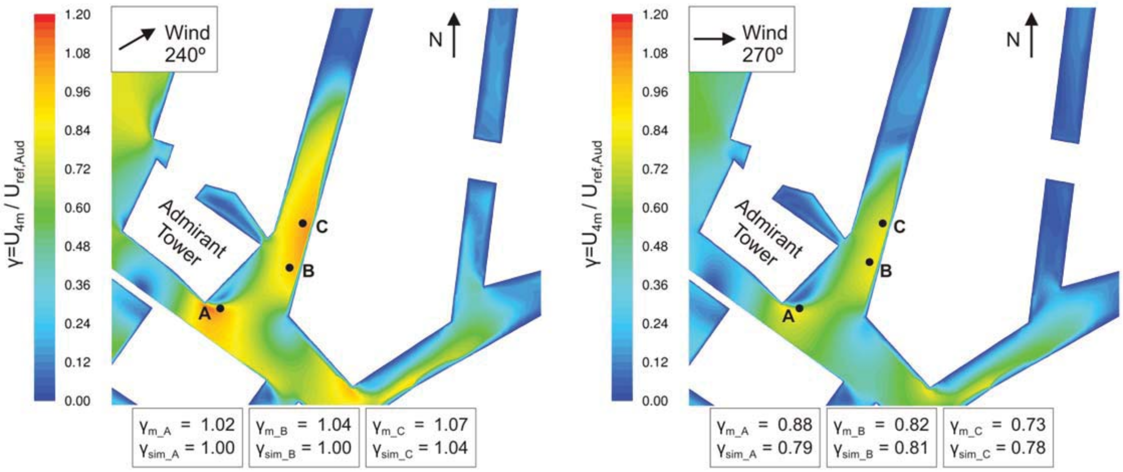

Figure 2. Comparison of measured (γ_m) and simulated (γ_{sim}) amplification factors in the area of interest.

5 WIND COMFORT ASSESSMENT WITH THE DUTCH WIND NUISANCE STANDARD NEN8100

The Dutch wind nuisance standard (NEN 8100) applies a discomfort threshold for the hourly mean wind speed (U_{THR}) of 5 m/s for all types of activities. Depending on the exceedance probability P of the threshold wind speed, the code defines five quality classes of wind comfort A–E (Table 1). These quality classes define a good, moderate or poor wind climate for the activities traversing, strolling and sitting (Willemsen and Wisse, 2007). 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 pedestrian level wind speed amplification factors ($\gamma = U/U_{ref,60m}$) from the CFD simulations (see Figure 3 for wind directions 60° and 240°). 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 comfort criterion has a threshold of 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.

Table 1: Criteria for wind comfort according to the Dutch wind nuisance standard NEN 8100 (2006)

$P(U_{THR} > 5$ 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

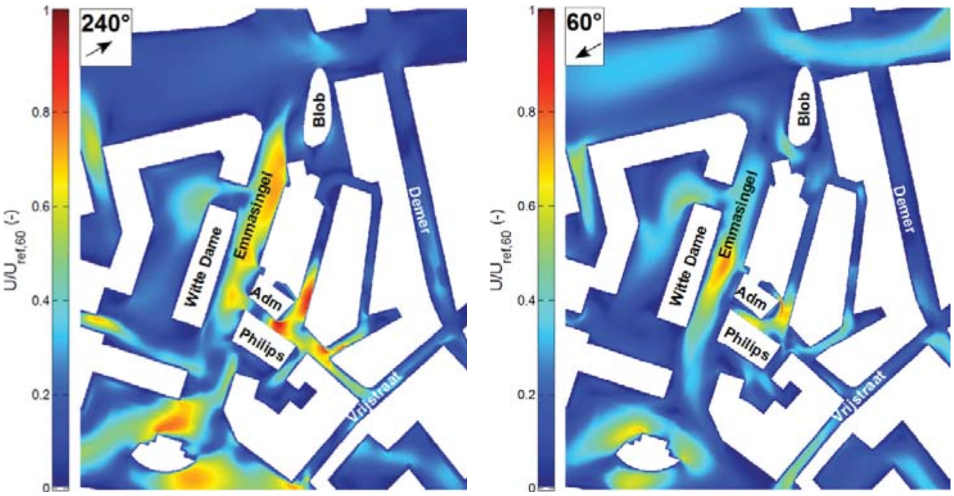

Figure 3. Simulated pedestrian level (z=1.75 m) wind speed amplification factors ($\gamma = U/U_{ref,60m}$) for the wind direction 240° (left) and 60° (right) from North.

6 RESULTS

Summing the percentage exceedances for all 12 wind directions, results in Figure 4a for the current situation. Here the annual exceedance probabilities for wind nuisance and the accompanying quality classes according to the Dutch Standard NEN 8100 are given. The map with wind classes at pedestrian level in the current situation (Figure 4b) shows rather large areas with quality class D around the corners of the tower. These areas have a moderate wind climate for traversing and a poor wind climate for both strolling and sitting. Because a shopping street is typically a place for strolling, measures should be taken to change the wind climate in these areas to be at least moderate for strolling (= quality class C or better).

Figure 5 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 most of the wind at 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 clearly 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 and the east-southeast side are studied. Four different canopies ascending in size are shown in Figure 6. 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 6 (0 – 7%) differs from the color scale in Figure 4 (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, as illustrated in Figure 7. 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. Another part of the solution is closing a pedestrian level opening at the northeast corner of the Admirant Tower to decrease local wind velocities at northeast wind directions.

With these solutions the wind quality classes in the walking area around the Admirant Tower become A and B (see Figure 8) while quality class C was foreseen as an already appropriate solution for this area. The wind climate is now expected to be good for traversing and strolling.

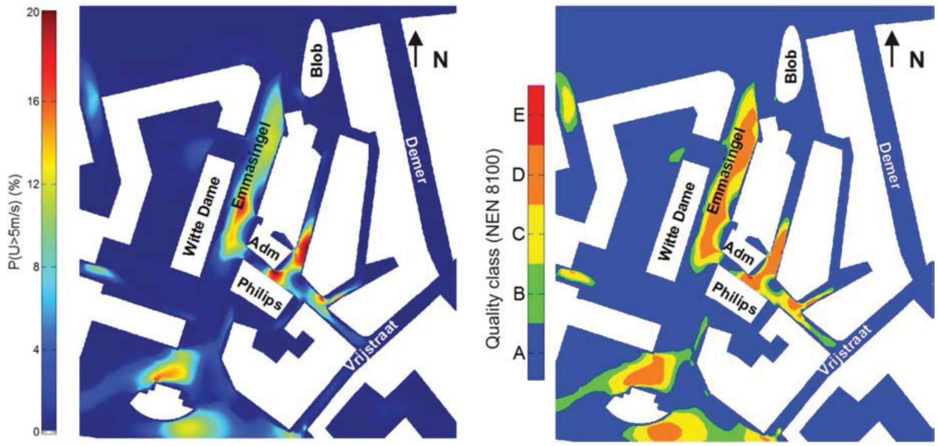

Figure 4. Annual exceedance probabilities for wind nuisance and the accompanying quality class according to the Dutch Standard NEN 8100, in the current situation.

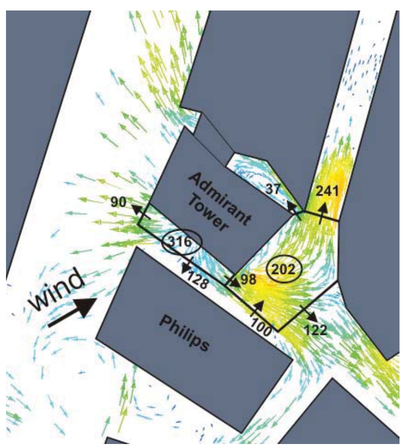

Figure 5. Simulated volume flow rate (m^3/s) at wind direction 240° around the Admirant Tower. Vertical circled volume flow rates at 4.5 m height and the horizontal volume flow rates through the streets are given.

7 DISCUSSION

As mentioned in section 2, the choice of turbulence model was based on earlier validation studies and on the validation study in this paper. This paper did not include studies with other turbulence models, but further research could focus on the effects of the turbulence model on the resulting comfort classes. The same holds for the selection of the aerodynamic roughness lengths for the inlet profiles and the roughness height for the ground surface in the domain. Although it should be mentioned that the computational model in this study is very extensive, with many buildings surrounding the area of interest. This way, the surrounding buildings will have the largest impact on the flow approaching the area of interest, rather than the upstream aerodynamic roughness lengths.

Although it is known that thermal effects are also important for wind comfort (e.g. Stathopoulos 2006, Metje et al. 2008), wind comfort and safety generally only refer to the mechanical effects of wind on people (e.g., Lawson and Penwarden 1975, Willemsen and Wisse 2007). Also in the Dutch wind nuisance standard, only mechanical effects are considered. Further research and elaboration of the standard will be needed to include thermal effects into the comfort assessment procedure.

8 SUMMARY AND CONCLUSIONS

CFD simulations in combination with the Dutch wind nuisance standard proved to be a useful approach in improving pedestrian wind comfort around a high-rise building in an urban area. Firstly the whole-flow field data provided by CFD showed that the tower was the main cause of the wind nuisance problem, and secondly the use of CFD made it possible to implement different measures to prevent wind nuisance while keeping the boundary conditions the same. The quality of the simulations is ensured by:

1) a successful comparison with on-site measurements. The average difference between measured and simulated amplification factors ($=U_{4m}/U_{ref,Aud}$) for two prevailing wind directions (240° and 270°) is only 0.04 (see Figure 2).
2) the special care that is given to creating a high-quality and high-resolution grid, according to best practice guidelines, and to the assignment of boundary conditions.

Simulations combined with local wind statistics show that the southwest wind directions contribute most to the annual wind nuisance at pedestrian level. For these wind directions the Admirant Tower deviates the wind down to pedestrian level, where the wind 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. Another part of the solution is closing a pedestrian level opening at the northeast corner of the Admirant Tower to decrease local wind velocities at northeast wind directions. With these solutions the wind quality classes in the walking area around the Admirant Tower become A and B (see Figure 8) while quality class C was foreseen as an already appropriate solution for this area. The wind climate is now expected to be good for traversing and strolling.

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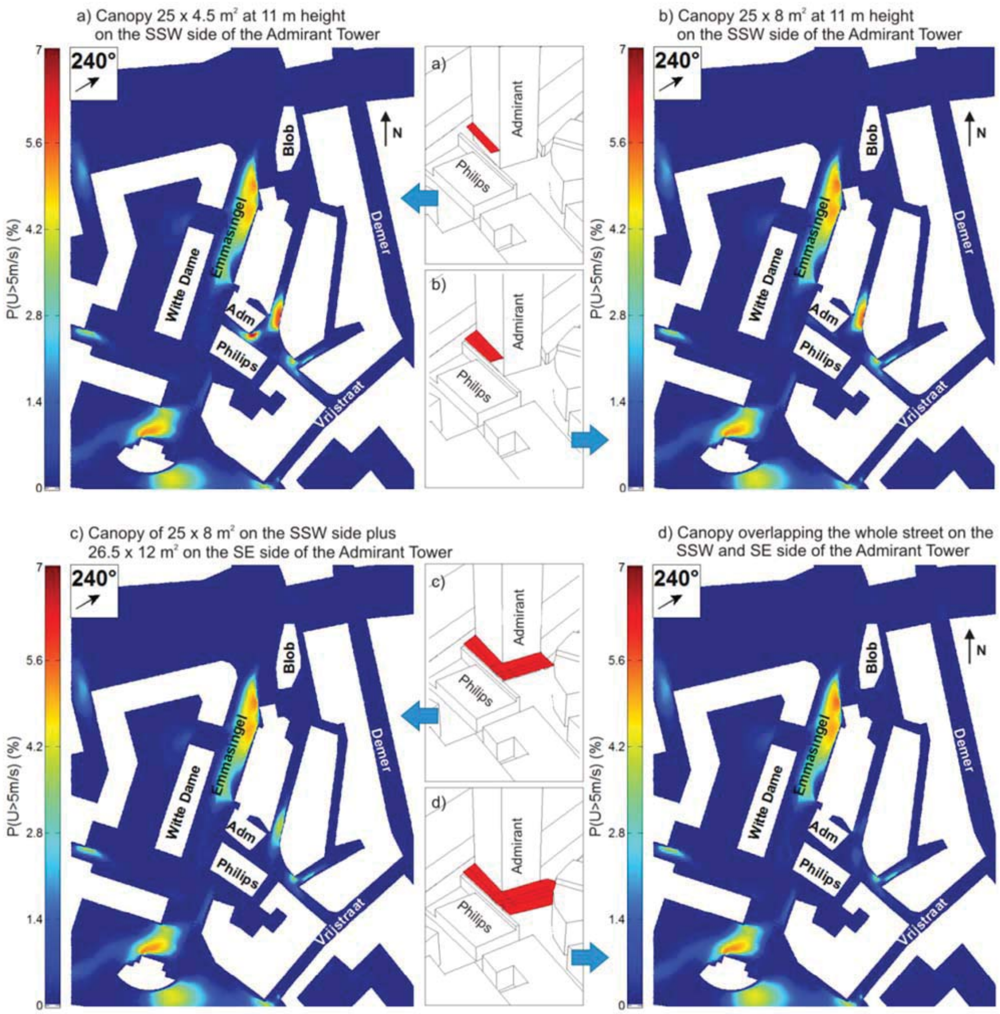

Figure 6. Percentage of hours per year that a threshold wind speed of 5 m/s is exceeded for four canopies attached to the Admirant Tower for a wind direction of 240°.

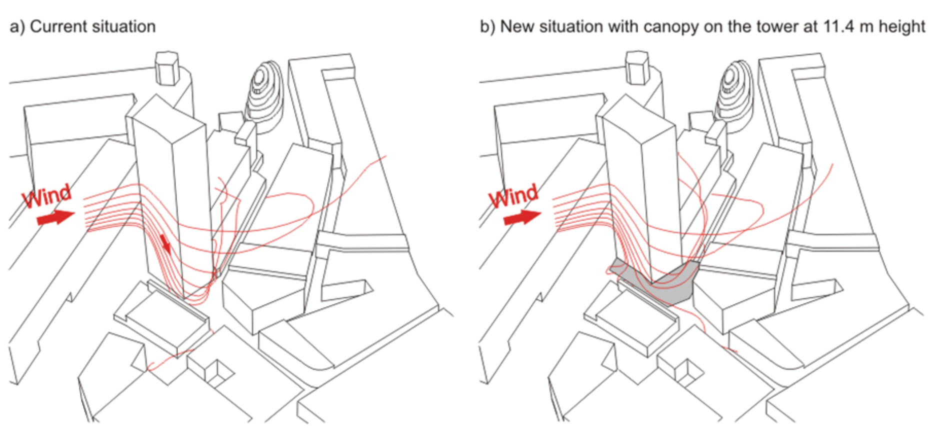

Figure 7. Pathlines of wind flow from a wind direction of 240°. a) In the current situation the tower deviates the wind down to pedestrian level while b) in the new situation the wind is directed over the building rooftops.

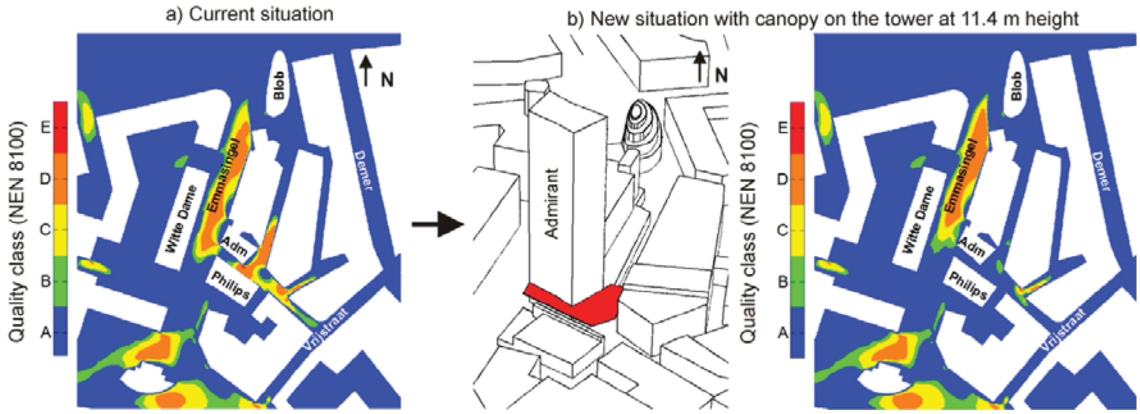

Figure 8. Wind climate quality classes NEN 8100 (A=good, E=poor) in a) the current situation and b) the new situation with a large canopy.

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