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Pedestrian wind comfort around buildings: comparison of wind comfort criteria based on whole-flow field data for a complex case study

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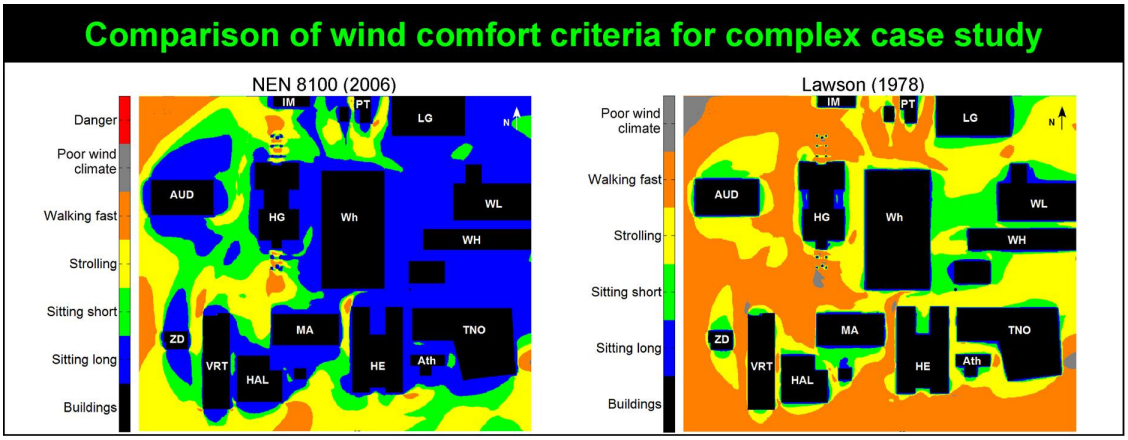
Graphical abstract:



Research highlights:

- Many wind comfort criteria exist, as well as a wind comfort standard, but case studies are lacking
- Extensive overview table with detailed comparison of four most complete wind comfort criteria
- Illustrative case study with whole-flow field data for comparison of different wind comfort criteria
- Comparison of different criteria shows very large differences in the assessment results
- Wind comfort standardization is very important, in particular concerning the comfort criterion

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Abstract
Assessment of pedestrian wind comfort around buildings requires the combination of wind statistics from a meteorological station, aerodynamic information and a comfort criterion. A wide range of different comfort criteria exist. In the past, several comparison studies of comfort criteria have been made. In the present paper, a different approach is pursued. The goal of this paper is threefold: (1) to provide an illustrative case study based on CFD as a framework for the comparison of different criteria; (2) to compare and evaluate the results by the different criteria as part of a complete wind comfort assessment study; and (3) to stress the importance of standardization of the wind comfort assessment procedure. The case study area is the campus of Eindhoven University of Technology. The 3D steady Reynolds-averaged Navier-Stokes (RANS) equations and the realizable k-ε model are used to provide part of the aerodynamic information. The CFD simulations are performed on a high-resolution grid based on grid-sensitivity analysis. Validation is conducted with on-site measurements. Part of the wind comfort assessment procedure is performed with the Dutch wind nuisance standard NEN 8100. The criteria compared in this study are the four complete criteria by Isyumov and Davenport (1975), Lawson (1978), Melbourne (1978) and NEN 8100 (2006). It is shown that the different criteria can lead to very different conclusions about the wind comfort. Because the outcome of wind comfort studies is often decisive in granting building permits, this illustrates the importance of wind comfort standardization, in particular concerning the comfort criterion.

Keywords: Wind nuisance and danger; Airflow; Urban area; Urban aerodynamics; Computational Fluid Dynamics (CFD); Built environment

1. Introduction

Wind comfort assessment studies consist of combining statistical meteorological data with aerodynamic information and a comfort criterion. The aerodynamic information is needed to transform the statistical meteorological data from the weather station to the location of interest at the building site, after which it is combined with a comfort criterion to judge local wind comfort. The aerodynamic information usually consists of two parts: the terrain related contribution and the design related contribution. The terrain related contribution represents the change in wind statistics from the meteorological site to a reference location near the building site. The design related contribution represents the change in wind statistics due to the local urban design, i.e. the configurations of buildings. It can be obtained by either wind tunnel modelling or numerical simulation with Computational Fluid Dynamics (CFD). CFD has some specific advantages compared to wind tunnel modelling, which will be briefly addressed in section 2, and which are the reasons for its use in the present paper.

A wide range of different wind comfort criteria exist. Most of these criteria consist of a threshold wind speed and a maximum allowed exceedance probability of this threshold. Many criteria also distinguish between various activities, such as sitting, strolling, walking fast, etc. In that case, either different values for threshold wind speed, or different maximum exceedance probabilities, or both, are imposed for these different activities. In the past, several comparisons of wind comfort criteria have been performed. Melbourne [1] suggested that the main difference in the early developed criteria was their way of presentation. Later studies [2,3] however suggested that Melbourne's criteria were much more restrictive than others. An extensive comparison study of wind comfort criteria was performed by Bottema [4]. Later, also Koss [5] provided a detailed overview of existing criteria. Bottema [4] compared most of the existing criteria based on a theoretical method, in which each criterion was converted to a maximum allowed wind amplification factor U/U_{pot}, where U is the local hourly

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mean wind speed and U_{pot} is the so-called potential wind speed. The potential wind speed is the hourly mean wind speed at an ideal meteorological station, at 10 m height over uniformly rough terrain with an aerodynamic roughness length z_0 = 0.03 m. Based on this comparison, he concluded that considerable differences exist between different criteria. In particular, he stated that the criteria of Gandemer [6], Isyumov and Davenport [7], Lawson [8] and Visser [9] are generally suitable for use in the Netherlands, while those of Williams and Soligo [10] were judged too lenient, and those of Melbourne [1] were too restrictive for most activities. While Bottema's approach provides a very valuable and systematic way of comparing different criteria, it also has some limitations. The wind amplification factor was assumed to be wind-direction independent, and the practical consequences of differences between criteria were rather difficult to interpret, visualise and communicate. In this respect, analysis of differences between criteria by means of illustrative case studies would be beneficial.

The goal of this paper is threefold: (1) to provide an illustrative case study based on CFD as a framework for the comparison of different wind comfort criteria; (2) to compare and evaluate the results by the different criteria as part of a complete wind comfort assessment study; and (3) to stress the importance of standardization of the wind comfort assessment procedure.

This comparison study is different from previous comparison studies, because of several reasons: (1) it is based on a complex case study; (2) it is performed based on whole-flow field data obtained by CFD; (3) it includes the recently established criteria in the Dutch wind nuisance standard; (4) it is based on a detailed categorization of the four different comfort criteria based on the original articles and on the level of activities in these criteria.

The case study area is the campus of Eindhoven University of Technology in the Netherlands. The 3D steady Reynolds-averaged Navier-Stokes (RANS) equations and the realizable k-ε model [11] are used to provide part of the aerodynamic information. Part of the wind comfort assessment procedure is performed based on the Dutch wind nuisance standard NEN 8100 [12,13]. Note that this paper is at least a partial answer to the call by Willemsen and Wisse [14], co-developers of the Dutch wind nuisance standard, for research and demonstration projects related to this standard.

In section 2, some comments are given on the use of CFD for wind comfort assessment studies. Section 3 briefly describes some main features of Dutch wind nuisance standard. Section 4 describes the four wind comfort criteria used in this study, as well as some main differences between these criteria. In section 5, the computational settings and parameters of the CFD simulations are outlined. Section 6 briefly presents the grid-sensitivity analysis, the results of the CFD simulations and the validation study. The results of the wind comfort assessment with the Dutch wind nuisance standard are given in section 7, while section 8 compares the results obtained with the four different comfort criteria. Finally, sections 9 (discussion) and 10 (conclusions) conclude the paper.

2. Some comments on the use of CFD for wind comfort assessment studies

In the past, several CFD studies of pedestrian-level wind conditions around buildings and/or in complex urban environments have been performed [15-32], generallybased on the steady RANS. Most studies included a comparison of the CFD results with wind tunnel measurements for the same building or urban configuration [16-18,21-24,28,30]. Others applied so-called sub-configuration validation [26,31]. This refers to performing validation for simpler generic building configurations that represent sub-configurations of the more complex urban configuration. For these generic configurations, wind tunnel measurements are generally available in the literature. Pedestrian-level wind studies in complex urban environments in which CFD results are compared with field measurements – as opposed to wind tunnel measurements – are very scarce. One such study was performed by Yoshie et al. [30], who compared CFD simulations with field measurements performed with 3-cup anemometers in 1977 in the Shinjuku Sub-central Area in Tokyo [33,34]. Two other studies of this type were performed by Blocken and Persoon [32] and by Blocken et al. [29].

CFD has been employed on a few occasions in the past as part of complete wind comfort assessment studies, i.e. including the wind statistics and evaluation by a comfort criterion (e.g. [22,25,26,29,31,32]. CFD offers some specific advantages compared to wind tunnel testing. It does not suffer from scaling problems and similarity constraints, because simulations can be performed at full scale. This can become important for extensive urban areas/models, such as in the case study in this paper. The availability of whole-flow field data from CFD is particularly important for the comparison of different wind comfort criteria, as will be shown later in this paper. However, CFD also has some important disadvantages. Especially the reliability and accuracy of CFD are important concerns. In this respect, the use of CFD in wind comfort studies has received strong support from several international initiatives that focused on the establishment of best practice guidelines, which are either general guidelines (e.g. [35-38]) or guidelines specifically intended for pedestrian wind conditions around buildings [29,30,39-44]. Note that these best practice guidelines mainly focused on RANS simulations. Strong support has also been provided by specific guidelines such as those for the simulation of equilibrium atmospheric boundary layers (e.g. [27,42,45-49]) and the generation of high-resolution and high-quality

computational grids (e.g. [50,51]). It is very important that the CFD simulations are accompanied by grid-sensitivity analysis and by validation by comparison with high-quality wind tunnel data and/or on-site measurements [29,30,35-38,41-44,52,53]. Important requirements for validation data have been provided by Schatzmann et al. [54] and Schatzmann and Leitl [55].

Studies to assess the accuracy of steady RANS CFD for predicting pedestrian-level wind speed have been reviewed by Blocken et al. [52]. Based on detailed comparison studies between CFD and wind tunnel experiments by Yoshie et al. [30] and Blocken and Carmeliet [31], the following common observation was found: steady RANS simulations with the standard k-ε model [56], the Kato-Launder k-ε model [57], the Renormalization Group (RNG) k-ε model [58] and the realizable k-ε model [11] all systematically showed that the amplification factor U/U_0 (which is the ratio of the local pedestrian-level wind speed U to the wind speed U_0 that would occur at the same position without buildings) is generally predicted with a high accuracy of 10-15% in the regions where $U/U_0 > 1$, while the predicted wind speed is generally significantly underestimated by CFD where $U/U_0 < 1$, at some locations by a factor 5 and more. Because the areas with high amplification factor are those that are most important in wind comfort studies, steady RANS could be considered a suitable method for such studies. The reason is that in case of wind comfort criteria with relatively high wind speed threshold value (e.g. $U_{THR} = 5$ m/s), regions with low U/U_0 will often not contribute substantially to the total exceedance discomfort probability, exactly because of their low amplification factor. In addition, it should be noted that RANS has some considerable advantages compared to Large Eddy Simulation (LES). On the one hand, LES has been shown – when applied correctly – to be more accurate, especially in regions with low U/U_0, because it can capture the inherently unsteady features of the flow field, such as separation regions on building facades and roofs and vortex shedding in the wake of buildings (e.g. [15,59,60]). On the other hand, LES is more complex and much more time-consuming than steady RANS. Yoshie et al. [30] mentioned that LES is still considered out of reach for practical pedestrian-level wind studies in actual urban environments. This is mainly attributed to the much larger calculation time. For pedestrian-level wind studies, simulations need to be performed for many (e.g. 12 or 16) wind directions, and this needs to be repeated for configurations with remedial measures implemented [30]. For all these reasons, the 3D steady RANS approach is considered to be a suitable approach for wind comfort assessment studies, and it will be used in the present paper. In particular, CFD is preferred over wind tunnel testing for the comparison of different comfort criteria, because it provides whole-flow field data and because of the extent of the case study area, which would require too large scaling factors and the associated similarity problems in the wind tunnel.

3. Some comments on the Dutch wind nuisance standard

In 2006, a standard for wind comfort (NEN 8100 [12]) and a new practice guideline (NPR 6097 [13]) were published in the Netherlands based on extensive research work by Verkaik [61,62], Willemsen and Wisse [14,63], Wisse and Willemsen [64], Wisse et al. [65], and others. One of the main intentions of the standard was to provide a uniform approach for wind comfort assessment in the Netherlands, concerning the use of statistical meteorological data, the acquisition and application of the aerodynamic information and the comfort criterion. This was meant to avoid different consultancy advice (in the form of different wind comfort assessment for the same building or urban configuration/situation) from different consultancy companies or institutes, which is clearly unwanted. The standard contains an improved and verified transformation model for the terrain related contribution that can provide the wind statistics at every location in the Netherlands, however without including the local building aerodynamic effects, which are part of the so-called design related contribution. A very special feature of the standard is that it allows the user to choose between wind tunnel modelling or CFD to obtain the design related contribution. This fact can be considered as a milestone towards the acceptance of CFD in wind comfort studies. Note however that the standard correctly points out the importance of quality assurance, both for CFD and for wind tunnel studies.

The Dutch wind nuisance standard also contains one wind comfort criterion and one wind danger criterion, albeit split up into different categories for different activities. The comfort criterion in the standard is based on a threshold value for the hourly mean wind speed of $U_{THR} = 5$ m/s for all types of activities. This value is relevant for mechanical pedestrian wind comfort and is also based on interviews with shop owners as discussed by Lawson and Penwarden [66]. Note that, although it is known that thermal comfort is also important (e.g. [67,68]), wind comfort and wind safety generally only refer to the mechanical effects of wind on people (e.g. [14,66]).

The exceedance probability P of this threshold value determines the grade or "quality class" (A to E) of the local wind climate (Table 1). The judgement of the local wind climate ("good, moderate, poor") of a certain class depends on the activity (traversing, strolling or sitting). The safety criterion has a threshold $U_{THR} = 15$ m/s and a maximum allowed exceedance probability of 0.3% (Table 2). 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 ($\gamma = U/U_{ref,60m}$) as design related contribution from wind tunnel experiments or CFD simulations. The reference wind speed value ($U_{ref,60m}$) is the value of the inlet wind speed profile at a height of 60 m;
(2) Convert threshold wind speed at pedestrian level to a threshold wind speed at a height of 60 m ($U_{THR,60m} = U_{THR}/\gamma$);
(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. The wind statistics for the 12 wind directions are provided by the Dutch Practice Guideline NPR 6097.

For more information on the standard, the reader is referred to the original documents [12,13] and the relevant publications [61-65]. For previous case study applications based on the Dutch wind nuisance standard, the reader is referred to [29,32].

4. Four complete wind comfort criteria

Four different wind comfort criteria are compared in this study, i.e. those by (1) Isyumov and Davenport [7], (2) Lawson [8], (3) Melbourne [1] and (4) the Dutch wind nuisance standard NEN 8100 [12]. While more criteria exist, these four criteria were selected in this study because they are considered as "complete" criteria, as they address a wide range of activities, including "sitting/standing long", "sitting short" and "strolling". The criteria all consist of a threshold value of the wind speed U_{THR} and a maximum allowed exceedance probability P_{max} of this threshold value. For comparison purposes, we have clustered these criteria according to the activities for which they define a "moderate/tolerable" situation, and we have provided this information in an overview table (Table 3). Table 3 includes the original references, the comfort threshold U_{THR}, the maximum allowed exceedance probability P_{max} and the description of the relevant activities, based on quotes from the original references.

Table 3 distinguishes between four main categories of activities in terms of wind comfort: (A) Sitting long; (B) Sitting short; (C) Strolling; (D) Walking fast. Two additional categories are "Danger" and "Unacceptable – Poor wind climate", where the latter is considered for a situation that is unacceptable for all activities but not yet dangerous. Therefore this category is situated between category "D" and "Danger". The categorization in Table 3 was based on the categorization and description of different pedestrian activities by Koss [5]. However, the clustering operation which resulted in Table 3 was not straightforward and unambiguous, for several reasons. The reasons and the main decisions/choices made in this paper to establish this categorization are outlined below.

- The comfort and danger criterion by Melbourne [1] uses exceedance probabilities based on daylight hours. Because tables of wind statistics as provided by meteorological institutes generally do not differentiate between day and night time, it was necessary to convert the criterion by Melbourne to combined day time and night time. This has been done by doubling the percentages of the exceedance probabilities in the criterion by Melbourne [1]. This means one daylight hour is made equal to 2 hours a year, both night and day time (= (2h/8760h)x100% = 0.022%; see Table 3).
- The descriptions of activities in the different comfort and danger criteria are not always consistent and sometimes partially overlapping. Three examples are mentioned: (1) The Dutch standard [12] applies the term "sitting long" for sitting in the park but not for sitting on a restaurant or cafe terrace. For the latter type of activity, it mentions that extra measures like screens are needed for a "good" wind climate but no actual comfort criteria are provided. Therefore, we have categorized the Dutch quality class A ("good" wind comfort for sitting in parks) as "moderate" for sitting long on e.g. terraces. (2) While the Dutch criterion can be rather lenient for "sitting long", the criterion by Lawson might be rather restrictive since the wind climate described is tolerable for covered areas, excluding uncovered terraces. (3) Melbourne calls the wind climate at which people begin to get blown over "completely unacceptable" while others use the term "dangerous". These descriptions have been combined in the category "danger" in Table 3.
- The comfort criterion by Isyumov and Davenport [7] applies a maximum exceedance probability of "1/week" for tolerability of wind climate for certain activities. The associated exceedance probability is said to be 1.5% but it is unclear how this value was obtained. 1 hour a week would be 0.6% (1/168x100%), a value also used by Lawson [8] when comparing his comfort criteria with criteria by Davenport. However, in the present paper, we use the exceedance probability of 1.5% as mentioned in the original article (Isyumov and Davenport [7], page 414). This choice is indicated in Table 3.
- The comfort criteria by Isyumov and Davenport [7] and Lawson [8] use the Beaufort scale as wind speed threshold. However, the Beaufort scale contains an interval of values for wind speed. As a result, the exact value of the wind speed threshold is not clear. In the present paper, we use the same threshold values as Isyumov and Davenport [7] that are converted from miles per hour to meter per second as shown in Table 4. Isyumov and Davenport ([7], page 408) already provided the translation from Beaufort scale at 33 ft (10 m)

to pedestrian level (6 ft – 1.8 m) using a conversion factor of 0.8. This means that the wind speed at pedestrian level is about 80% of the wind speed U_{10} at the reference height of 33 ft (10 m).

Based on the clustering operation which resulted in Table 3, a first comparison of the criteria can be made, focused on the type and value of the threshold wind speed and the value of the exceedance probability. This results in the following observations:

- The criteria by Isyumov and Davenport [7], Lawson [8] and Melbourne [1] use different values for U_{THR} but the same P_{max} for different activities, while NEN 8100 uses the same value for U_{THR} but different values for P_{max} for different activities.
- The criterion by Melbourne [1] differs from the other criteria because it considers "gustiness" in the criterion, by addition of σ_u, which is the standard deviation of turbulent fluctuations.
- The criterion by Melbourne [1] also differs from the others because exceedance probabilities are restricted to one daylight hour a year, which implies a very small value for P_{max} (0.022%) which makes this criterion rather strict, in spite of the large threshold values for wind speed.
- The criteria by Isyumov and Davenport [7] and Lawson [8] use a similar value for P_{max}, but their choice for the wind speed threshold differs by one step in the Beaufort scale. This implies that the criteria by Isyumov and Davenport are less demanding than those by Lawson.
- The criterion by Melbourne [1] does not consider activity D and the criterion by Lawson [8] does not provide information about wind danger.

5. CFD simulations: computational settings and parameters

5.1. Computational geometry and domain

Figure 1 shows the campus of Eindhoven University of Technology, with indication of the abbreviated building names and average building heights. Figure 2 shows a few photographs of important buildings and building features that will receive specific attention in this paper: the HG building (Fig. 2a) with its characteristic through-passages at both ends and the high-rise PT building (Fig. 2b). Figure 3a, 3c and 3e show aerial photographs of the campus terrain. Figures 3a and 3b show the computational domain and Figures 3b, 3d and 3f show the computational geometry and parts of the computational grid. The explicitly modelled buildings (i.e. those that are modelled with their actual dimensions) are all buildings on the campus (see Fig. 2c) and some additional high-rise buildings situated southwest of the campus (see Fig. 3e-f). Different high-rise buildings are present on the campus terrain, but the highest building in the model is situated just outside this terrain, which is the 83 m high Kennedy Tower, indicated in Figure 3e. The central part of the computational domain has dimensions L x W x H = 1918 x 1430 x 830 m³. Attached to this central subdomain are an upstream and a downstream subdomain. The upstream domain length is kept as short as possible (5h, with h the height of the highest explicitly modelled building, i.e. the Kennedy Tower) to avoid the occurrence of unintended streamwise gradients (e.g. [27,45-49]), while still satisfying the best practice guidelines by Franke et al. [41-43] and Tominaga et al. [44]. The downstream domain length (15h) allows the development of the wake regions behind the buildings, which is beneficial for convergence of the simulations. To satisfy these requirements for upstream and downstream domain length, different computational domains have been made for simulations with different wind directions. The domain height, for all wind directions, is 830 m, which is equal to 10h. The resulting computational domain for wind direction from west is shown in Figure 3a and 3b. The actual area of interest is indicated by the dashed rectangle in Figure 3a. Yoshie et al. [30] advise that the reproduction range of surrounding urban blocks around the area of interest would be satisfactory for practical application if at least one surrounding block is explicitly modelled. Note that in the present case study even more buildings are explicitly modelled. This has been done in view of the future use of this model for other areas on the campus terrain.

5.2. Computational grid

Special care was given to the development of a high-quality and high-resolution grid that consists only of hexahedral and prismatic cells and that does not contain any tetrahedral or pyramidal cells. The grid was constructed using the grid generation technique presented by van Hooff and Blocken [51], which allows a large degree of control over the quality of the grid and its individual cells. Images of the grid of the campus terrain are shown in Figure 3b, 3d and 3f. While generating this type of grid that has only hexahedral and prismatic cells requires a considerable effort, it avoids the well-known convergence problems that are associated with hybrid grids with tetrahedral cells, especially when the required second-order discretisation schemes are used. This grid generation technique was successfully used earlier for modelling complex building and urban configurations [29,51,69-78].

The computational grid used for this study consists of 7,554,091 cells for the domain for west and southwest wind directions. For other wind directions, slightly different total cell numbers were obtained. Note that in accordance with the best practice guidelines [42,44], at least three to four cell layers should provided below pedestrian height (1.75 m), at which the results will be evaluated. Here 5 cell layers are implemented. The grid was based on a detailed grid-sensitivity analysis that will be reported in section 6.1, along with the simulation results.

5.3. Boundary conditions

At the inlet of the domain, neutral atmospheric boundary layer profiles of mean wind speed, turbulent kinetic energy and turbulence dissipation rate are imposed. These profiles are linked to the aerodynamic roughness length z_0 of the terrain upstream of the computational domain. Figure 4 shows the plan view of the wider surroundings with a radius of 10 km around the campus. The computational domain is indicated by the central white rectangle. This view with indication of the land use is needed to estimate the value of z_0. Given the gradual development of internal boundary layers due to roughness changes, a 10 km upstream fetch is required to determine z_0. This estimate is performed for the twelve wind direction sectors, based on the updated Davenport roughness classification [79].

The vertical profile of mean wind speed is given by the logarithmic law: $U(z) = (u^*_{ABL}/\kappa)\ln((z+z_0)/z_0)$, where u^*_{ABL} is the friction velocity, κ the von Karman constant (0.42) and z the height coordinate. The reference wind speed is 5 m/s at 10 m height. 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 turbulent kinetic energy k is calculated using the longitudinal turbulence intensity (I_u) and assuming that the standard deviations of the turbulent fluctuations in the three directions are similar ($\sigma_u = \sigma_v = \sigma_w$): $k(z) = 3/2(I_u U(z))^2$. The inlet turbulence dissipation rate ε is given by: $\varepsilon(z) = (u^*_{ABL})^3/(\kappa(z+z_0))$.

At the outlet, zero static pressure is specified. At the sides and the top of the domain, symmetry boundary conditions are imposed (i.e. zero normal velocity and gradients). At the walls, the standard wall functions by Launder and Spalding [80] with the sand-grain roughness modification by Cebeci and Bradshaw [81] are used. Within the domain, different types of "walls" or rough surfaces are considered, as indicated in Table 5 for building surfaces (facades and roofs), streets and parking areas, grass and the surrounding terrain in which buildings are not explicitly modelled. The roughness parameters for each surface type are given in Table 5. The wall function inputs are the parameters k_S (equivalent sand-grain roughness height) and C_S (roughness constant). These parameters are determined from the local values of z_0. The relationship between z_0 and the parameters k_S and C_S was derived by Blocken et al. [46]. For Fluent 6.3, this relationship is $k_S = 9.793 z_0/C_S$.

5.4. Other parameters

The CFD simulations are performed using the commercial CFD code Fluent 6.3.26 [82] and the 3D steady RANS equations. Closure is provided by the realizable k-ε turbulence model [11]. 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. Convergence is obtained when the scaled residuals showed no further reduction with increasing number of iterations and at that time the residuals reached the following minimum values; x-, y- and z-momentum: 10^{-8}, k and ε: 10^{-7} and continuity: 10^{-6}.

6. CFD simulations: results and validation

6.1. Grid-sensitivity analysis

A grid-sensitivity analysis is conducted in which two additional grids, a coarser grid with 2,598,602 cells and a finer grid with 12,392,255 cells, were constructed. The three grids are shown in Figures 5a-c. The mean wind speed ratios ($U_{mp}/U_{ref,Aud}$) and the local wind directions obtained on the different grids are compared with each other at different positions for the prevailing southwest wind direction ($\varphi = 215°$). The positions are indicated in Figure 5d; these are the positions V, H and positions 1-12 were on-site measurements were made, and 16 extra positions along the two horizontal lines in Figure 5d. The wind speed ratio is defined as the local mean wind speed U divided by the mean wind speed at the reference position $U_{ref,Aud}$ at the top of the meteorological mast on the Auditorium Building (AUD), at a height of 44.6 m. Figure 5e and 5f show that the differences between the coarse grid and the basic grid are significant whereas the differences between the finer and basic grid are small. This indicates that the basic grid is a good compromise between computational accuracy and computational cost. The basic grid is therefore retained for further analysis.

6.2. Mean wind speed ratios

The analysis of the wind-flow patterns is based on the knowledge of the main generic building configurations that can give rise to pedestrian-level wind comfort problems as shown in Figure 5 [83]:

(a) Passage through a building: the overpressure area upstream and the underpressure area downstream are short-circuited by the through-passage. This generally yields a passage jet with high wind speed amplification. Note that the same mechanism yields the so-called corner streams, i.e. the high wind speed regions around the upstream corners of a building, from the overpressure area upstream of the building to the underpressure area downstream of the building.

(b) Passage between two parallel buildings: same mechanism of pressure short-circuiting by means of passage jet, although generally less pronounced then in the case of a through-passage.

(c) Passage between two parallel shifted buildings: similar mechanism as in the previous configurations.

Figures 7 and 8 show the pedestrian-level wind speed ratios $U/U_{ref,60m}$ for the twelve wind direction sectors, from 0° (from north) to 330° in steps of 30°. Note that these wind speed ratios are defined as the local mean wind speed at pedestrian level U divided by the mean wind speed at 60 m height. This definition is different than that of the amplification factors U/U_0 in section 2 and the wind speed ratios $U/U_{ref,Aud}$ in sections 6.1 and 6.3. The reason is that the ratio $U/U_{ref,60m}$ is the one that is required in the wind comfort assessment procedure in NEN 8100. Figures 7 and 8 show that the wind-flow pattern is complex and that it is dominated by regions with low wind speed ratios that are interspersed with smaller areas of much higher wind speed ratios. In spite of the complexity of the urban area, similar consequences of pressure short-circuiting, as shown in Figure 6 for the generic configurations, can also be noticed in Figures 7 and 8. The following specific observations are made. They are mentioned systematically for every wind direction to explain and highlight problematic areas in terms of wind nuisance in a complex urban environment, and to show that the three generic configurations mentioned above are represented in the case study:

- Figure 7a (φ = 0°): Large wind speed ratios are found in the fairly open north-west part of the campus, in the passage between the HG building and the AUD building and around the upstream corners of the VRT building. The east side of the campus is to a large extent sheltered from wind.
- Figure 7b (φ = 30°): Overall, fairly low wind speed ratios are observed for this wind direction. Locally higher values are found in the corner streams of the PT and HG buildings.
- Figure 7c (φ = 60°): High wind speed ratios are present in the north part of the campus terrain and in the corner streams around the high-rise PT and the HG buildings.
- Figure 7d (φ = 90°): High wind speed ratios are found in the passage between the upstream low-rise buildings, in the corner stream around the PT and VRT buildings and in the through-passages at both ends of the HG building. Although the HG building is to some extent sheltered by the upstream buildings, due to its large height it captures a significant portion of the oncoming wind and deviates it downwards, where it is channelled through the passages underneath this building.
- Figure 7e (φ = 120°): High wind speed ratios are observed around the corners of several buildings, including TNO, HE, VRT, PT and HG.
- Figure 7f (φ = 150°): High wind speed ratios are present around the corners of the buildings TNO, HE, VRT, HG and others.
- Figure 8a (φ = 180°): High wind speed ratios are observed on the west side of the campus. In particular, high wind speed ratios are found around the corners of the VRT and AUD buildings, and also around the corners of the TNO, HE and HG buildings.
- Figure 8b (φ = 210°): The corners streams around the buildings VRT, HE and TNO buildings are clearly visible, as well as the jets in the passages between ZD and VRT and between MA and HE. The HG building and its through-passages are in the wake of the high-rise VRT building, and therefore no high wind speed ratios are present in these passages for this wind direction. Note the corner stream at the PT building; although this building is located downstream, it is one of the highest buildings on campus and its height (54.8 m) causes its higher floors to be sufficiently exposed to the oncoming wind to capture it and deviate it downwards.
- Figure 8c (φ = 240°): High wind speed ratios are mainly found at the corner of the VRT building, and to some extent in the through-passages of the HG building.
- Figure 8d (φ = 270°): High wind speed ratios at the upstream corners of the VRT building, in the through-passages of the HG building, around the corners of the HG building and around the corners of the PT building.
- Figure 8e (φ = 300°): Due to the relatively open exposure north-west of the campus and due to the position of three of the highest buildings (PT, HG and VRT) on the west side, very high wind speed ratios are found here. In particular in the through-passages through the HG building and in the corners streams around the PT

and VRT building. Further downstream, the wind speed ratios are much lower, due to the shielding effect of the upstream buildings.

- Figure 8f (φ = 330°): Again due to the relatively open upstream exposure, high values are found in the through-passages under the HG building and in the corner streams around the AUD and VRT building.

6.3. Validation

For validation purposes, full-scale on-site measurements have been performed during six months at 15 different positions on the campus terrain using 3D ultrasonic anemometers. Figure 5d shows the position of three fixed measuring positions (V near building VRT, H near building HG and the reference position A on top of a mast on building AUD) and the positions of mobile posts (1-12) which were used on several windy days in the measuring period. Note that, for practical/safety reasons, the fixed positions were placed above pedestrian level, i.e. V at 5.4 m and H at 8.9 m above ground level. The measurements and the model validation are described in detail in [29] and are therefore not repeated here in detail. Note that the measurements with the mobile posts had a duration of at least two hours during high wind speed conditions, as explained in [29], and were performed outside office hours to minimise disturbances due to vehicle and pedestrian traffic.

As mentioned in section 2, the performance of the RANS approach is quite good in the regions of high wind speed ratios, while it can strongly deteriorate in regions of low wind speed ratios. To illustrate this, Figure 9a shows the comparison between the simulated and the measured wind speed ratios ($U/U_{ref,Aud}$) at the two fixed measurement positions V and H. Every data point corresponds to a reference wind direction for which enough measurement data were available, i.e. all 12 wind directions except 90°. For the majority of the wind directions the difference between the simulated and measured wind speed ratios is smaller than 20% and for high wind speed ratios (> 0.6) most simulated values differ less than 10% from the measured wind speed ratios. The five outliers (deviation larger than 20%) are attributed to the high wind speed gradients at these positions and for these particular wind directions. Therefore, a small shift in measurement position will yield a large change in wind speed ratio. Figure 9b shows a similar comparison for the local wind directions. The simulated and measured wind directions generally match well, with differences between simulations and measurements that are generally within 30°. Note that since 360° = 0°, the two data points in the bottom right corner of Figure 9b actually do not imply a very large difference between the simulated and measured wind direction, although the differences are indeed larger than at the all other points: 68 ° (position V) and 102 ° (position H). These differences are attributed to the large gradients in wind direction at these specific measurement positions and for these wind directions.

7. Wind comfort assessment with the Dutch wind nuisance standard

The wind speed ratios reported in the previous section are used in combination with the wind statistics and the comfort criteria of the Dutch wind nuisance standard [12] in Table 1 and 2 to provide an assessment of wind comfort and wind safety/danger on the campus terrain. The wind statistics for the location of the Eindhoven university campus are obtained from the Dutch Practice Guideline NPR6097 [13] and are illustrated by means of wind roses in Figure 10. South-west is the prevailing wind direction, and this is even more pronounced for the higher wind speed values, as shown in Figure 10b. This implies that the wind directions 180°, 210°, 240° and 270° (also shown in Figure 8) will have the largest contribution to the discomfort exceedance probability.

Figure 11 shows the results of the wind comfort assessment procedure, by means of contours of the quality classes in the Dutch wind nuisance standard. The following observations are made:

- These contours show a strong similarity to those in Figures 8a, 8b, 8c and 8d, due to the large contribution of these wind directions to the discomfort probability.
- The main areas of wind nuisance correspond to the areas of high wind speed ratio discussed in section 6.2: the through-passages of the HG building, the corner streams around the PT, VRT, HG, ZD, HE and TNO building, and the jets in the passages between the VRT and ZD building, and between the MA and HE building. In these areas, wind comfort is classified with quality class C or D, which means a poor wind climate for sitting but good or moderate for traversing.
- The eastern part of the study area mainly has a quality class A, which means a good wind comfort for sitting. This is directly related to the prevailing southwest wind direction and the urban configuration of the campus. In addition, some areas in between have quality class B, which means moderate wind comfort for sitting, but good wind comfort for strolling and traversing.

Although no official enquiry has been conducted, these results correspond very well with the experiences and observations of staff and students of Eindhoven University of Technology. The park south of the AUD building is often used for activities because of its good wind comfort, while the areas under the HG building and near the VRT building are well-known wind nuisance areas, where parked bikes are often blown over. To our knowledge, no dangerous wind situations have ever been reported on the campus, which also supports the results in Figure

11. These experiences based on 6 years of on-site observations imply that the comfort criteria in the Dutch wind nuisance standard seem to provide a realistic and fairly accurate description of the actual wind conditions on the campus of Eindhoven University of Technology.

8. Wind comfort assessment with different criteria and comparison

The wind comfort assessment procedure in the Dutch wind nuisance standard is repeated, in which the comfort and danger criteria by NEN 8100 are replaced by those by Isyumov and Davenport [7], Lawson [8] and Melboure [1], respectively. It should be noted that σ_u in the criteria by Melbourne is obtained using $\sigma_u = (\frac{2}{3}k)^{0.5}$, where k is the simulated turbulent kinetic energy (m^2/s^2) at the position of interest. Figure 12 shows the results of applying the wind comfort assessment procedure with the different comfort criteria. In interpreting these figures, it should be noted that the categorization in Table 3 was used and that it was established based on the judgement of "tolerable/moderate" wind climate for different pedestrian activities. Therefore the colour contours in Figure 12 also represent this judgement for every activity indicated. The following observations are made:

- Overall, the application of the different criteria shows large differences in the resulting statements on wind comfort and wind danger. This confirms the importance of standardization of studies of wind comfort and wind danger, especially concerning the comfort and danger criteria.
- Figures 12b and 12c provide very similar contour shapes, however Figure 12c seems to be shifted one step upwards in the colourbar compared to Figure 12b. This corresponds to the statement in section 4 that the criteria by Isyumov and Davenport [7] and Lawson [8] use a similar value for P_{max}, but that their choice for the wind speed threshold differs by one step in the Beaufort scale. Therefore, the criteria by Lawson [8] are stricter than those by Isyumov and Davenport. Figure 11c indeed indicates that according to this criterion, a large part of the campus area would only be suitable for walking fast, while Figure 12b indicates that this area is generally also suitable for strolling.
- Figures 12a and 12b-c show rather similar contour shapes. Compared to the criteria by Isyumov and Davenport [7], the criteria by the Dutch wind nuisance standard NEN 8100 seem less strict, however it should be noted that the Dutch Standard actually does not specify any criteria for sitting on terraces at for instance cafes or restaurants [12]. For these places, NEN states that quality class A (blue) is not strict enough and extra screens should always be placed to avoid wind nuisance. The blue area here indicates that the area is suitable (good wind climate) for sitting long as one would expect when sitting on a bench in a park, but not necessarily for a restaurant terrace. For the criteria by Isyumov and Davenport [7] and also Melbourne [1], the blue coloured areas mean that there is a tolerable wind climate for sitting on a restaurant terrace. Lawson's criterion is rather strict because for "sitting long", it gives an indication what wind climate is tolerable in covered areas [8]. In these covered areas the tolerance for wind is lower than in open areas where more wind is already anticipated by the public.
- Concerning the most problematic areas, only the criterion by Melbourne [1] identifies some areas of wind danger, while neither NEN 8100 nor Isyumov and Davenport [7] indicate areas of poor wind climate or wind danger. Note that all four criteria indicate the area under the Main Building (HG) to be one of the most problematic areas. According to Melbourne [1], this area is potentially dangerous, while NEN 8100 and Isyumov and Davenport [7] label it as tolerable for walking fast. The latter label corresponds with actual experiences on site. The criterion by Lawson [8] denotes this area partly as "poor wind climate" and partly as suitable for "walking fast". Some other potentially problematic areas are indicated by NEN 8100 as well as by Isyumov and Davenport [7] as only suitable for "walking fast". These are the corner streams at the VRT, PT, HE and TNO buildings and the area west of the ZD building.
- Concerning the best areas in terms of wind comfort, NEN 8100 provides the most positive outcome, indicating that a large part of the campus area is suitable for sitting long, while other large areas are suitable for sitting short and/or strolling. The second most positive outcome is provided by the criteria by Isyumov and Davenport [7]. These criteria only show a relatively small area to be suitable for sitting long, but fairly large areas to be suitable for sitting short and/or strolling. This is in clear contrast to the results obtained with the criteria by Lawson [8], where the largest part is labelled as only suitable for "walking fast". The criterion by Melbourne [1] on the other hand shows that a large part of the campus area is suitable for strolling, but on the other hand another large part is not labelled ("unclassified"), meaning that according to Melbourne [1], it is not suitable for strolling.

9. Discussion

In this paper, the four complete wind comfort criteria have been compared based on the case study of the Eindhoven University campus for which whole-flow field data were available from detailed CFD simulations. The main limitations of this study are:

- The study has been performed for the wind statistics of Eindhoven. Further research will consist of comparing the different criteria for a case study using different sets of wind statistics.
- The study has been performed for one particular case study. This limitation is considered less important than the previous one, because the case study includes many different types of buildings and it includes the main wind nuisance configurations and flow patterns shown in Figure 6 (jets in through-passages, jets in passages between buildings and corner streams) and addressed systematically in section 6.2. In addition, a wide range of wind speed ratios are present over the campus terrain, which indicates the suitability of the present case study for comparison of different criteria.
- This study did not have the intention to indicate which criterion is best, but to visualize the large and sometimes very large differences between different wind comfort criteria. It is likely that in different countries and regions, a different comfort criterion would be best to describe actual wind comfort and wind danger. However, irrespective of this fact, for a given country and region, it is clear that the assessment of wind comfort and wind danger should be performed with one specific choice of criterion, to avoid ambiguous results or different outcomes, depending on which criterion is used by consultancy offices and research institutes that perform the assessment.

Note that only the criterion by Melbourne [1] includes gustiness by addition of σ_u, which is the standard deviation of turbulent fluctuations, accompanied by a peak factor of 3.5. While there seems to be a consensus in the scientific literature that gustiness is important for wind nuisance and especially for wind danger, the value of the peak factor to be used remains an issue of debate [4]. Many comfort criteria, including the one in the Dutch wind nuisance standard, only include the mean wind speed. In these criteria, it is possible that gustiness is included implicitly by means of a lowered threshold value of the mean wind speed or a lowered discomfort exceedance probability. The difficult to accurately reproduce turbulence and turbulence spectra in wind tunnels and CFD simulations might have been an additional argument to only include the mean wind speed in many existing criteria.

10. Conclusions

This study showed that the different criteria can lead to very different conclusions about the wind comfort situation in the complex urban area under study. This case study is considered representative because it included examples of the three main wind nuisance configurations.. The criteria by Lawson [8] and by Melbourne [1] were shown to be most restrictive, while the criteria by Isyumov and Davenport [7] showed the best agreement with those of NEN 8100. The latter criterion is considered to be the most lenient of the four complete criteria considered in this comparative study. The resulting wind comfort predictions sometimes shift two classes; from a wind climate that is tolerable for “sitting long” according to NEN 8100 to a wind climate that is only tolerable for “strolling” according to Lawson [8] and Melbourne [1]. Note that even the criteria by NEN 8100 and Isyumov and Davenport [7], which correspond best to each other, locally can yield differences up to two activity classes. Nowadays, many urban authorities only grant a building permit after a wind comfort assessment study has shown that the negative consequences of the new building for the wind environment remain limited. The choice of the comfort criterion can therefore have major impact on the decision whether or not remedial measures should be considered, whether or not a building permit will be granted and whether or not the final design will provide a tolerable wind climate. This stresses the importance of standardization of the wind comfort assessment procedure, especially concerning the comfort criterion. The sometimes ambiguous and subjective interpretation of existing wind comfort criteria also highlights the importance of providing complete information about the wind comfort criterion in every wind comfort assessment report or study.

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Table 1. Criteria for wind comfort according to NEN 8100 [12].

$P(U_{THR} > 5$ 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**

Table 2: Criteria for wind danger according to NEN 8100 [12].

$P(U_{THR} > 15$ m/s (in % hours per year)	Grade
0.05 - 0.30	Limited risk
≥ 0.30	Dangerous

Table 3: Different wind comfort and wind danger criteria consisting of wind speed thresholds and maximum allowed exceedance probabilities for a tolerable wind climate for different pedestrian activity categories.

Reference	**Threshold (moderate/tolerable wind climate)**	**P_{max}**	**Description of activity**
***A (Sitting long)**: Sitting for a long period of time, laying in steady position, pedestrian sitting, terrace, street café or restaurant, open field theatre, pool*			
Isyumov & Davenport (1975) [7]	U > 3.6 m/s (3 Bft)	1.5 % (1/week)	"Tolerable climate for sitting - long exposure (outdoor restaurants, bandshells, theatres)"
Lawson (1978) [8]	U > 1.8 m/s (2 Bft)	2 %	"Tolerable for covered areas"
Melbourne (1978) [1]	$U + 3.5\sigma_u > 10$ m/s	0.022% (2 h/year)	"Generally acceptable for stationary, long-exposure activities (outdoor restaurants, theatres)"
NEN 8100 (2006) [12]	U > 5 m/s	2.5 %	Quality Class A: "good climate for sitting long (parks)". Note: the Dutch Standard does not focus on café or restaurant terraces
***B (Sitting short)**:Pedestrian standing, standing/sitting over a short period of time, short steady positions, public park, playing field, shopping street, mall*			
Isyumov & Davenport (1975) [7]	U > 5.3 m/s (4 Bft)	1.5% (1/week)	"Tolerable climate for standing, short exposure (parks, plaza areas)"
Lawson (1978) [8]	U > 3.6 m/s (3 Bft)	2 %	"Tolerable for pedestrian stand around"
Melbourne (1978) [1]	$U + 3.5\sigma_u > 13$ m/s	0.022% (2 h/year)	"Generally acceptable for stationary short-exposure activities (window shopping, standing or sitting in plazas)"
NEN 8100 (2006) [12]	U > 5 m/s	5 %	Quality Class B: "moderate climate for sitting long (parks)"
***C (Strolling)**: Pedestrian walking, leisurely walking, normal walking, ramble, stroll, walkway, building entrance, shopping street, mall*			
Isyumov & Davenport (1975) [7]	U > 7.6 m/s (5 Bft)	1.5 % (1/week)	"Tolerable climate for strolling, skating (parks, entrances, skating rinks)"
Lawson (1978) [8]	U > 5.3 m/s (4 Bft)	2 %	"Tolerable for pedestrian walk-thru"
Melbourne (1978) [1]	$U + 3.5\sigma_u > 16$ m/s	0.022% (2 h/year)	"Generally acceptable for main public access-ways"
NEN 8100 (2006) [12]	U > 5 m/s	10 %	Quality Class C: "moderate climate for strolling"
***D (Walking fast)**:Objective business walking, brisk or fast walking, car park, avenue, sidewalk, belvedere*			
Isyumov & Davenport (1975) [7]	U > 9.8 m/s (6 Bft)	1.5% (1/week)	"Tolerable for walking fast (sidewalks)"
Lawson (1978) [8]	U > 7.6 m/s (5 Bft)	2 %	"Tolerable for roads, car parks"
NEN 8100 (2006) [12]	U > 5m/s	20 %	Quality Class D: "moderate climate for walking fast"
***Unacceptable, poor wind climate** → region in between D and Danger*			
Danger		**P_{min}**	
Isyumov & Davenport (1975) [7]	U > 15.1 m/s (U > 8 Bft)	0.01% (1/year)	"Dangerous"
Melbourne (1978) [1]	$U + 3.5\sigma_u > 23$ m/s	0.022% (2 h/year)	"Completely unacceptable – the gust speed at which people get blown over"
NEN 8100 (2006) [12]	U > 15 m/s	0.05 %	"Limited risk" and "dangerous"

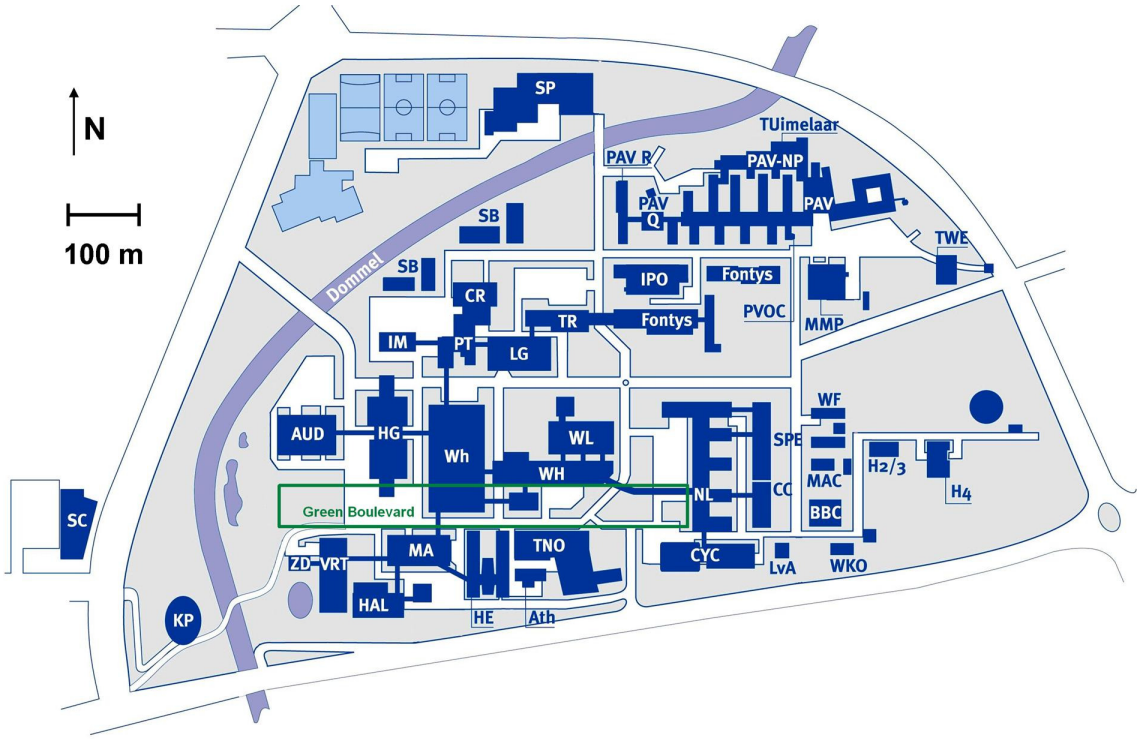
Table 4. Translation of the Beaufort scale at 6 ft. (1.8 m) from miles per hour (Isyumov and Davenport, [7]) to m/s.

Force (Bft)	Description	Wind speeds (miles/hour)		**Wind speeds (m/s)**		Specifications
		Mean	Limits	**Mean**	Limits	
2	Light breeze	4	3-6	**1.8**	1.3-2.7	Wind felt on faces; leaves rustle
3	Gentle breeze	8	6-10	**3.6**	2.7-4.4	Leaves and small twigs in constant motion; wind extends light flag
4	Moderate breeze	12	10-15	**5.3**	4.4-6.7	Raises dust and loose paper; small branches are moved
5	Fresh breeze	17	15-20	**7.6**	6.7-8.9	Small trees in leaf begin to sway
6	Strong breeze	22	19-25	**9.8**	8.4-11.1	Large branches in motion; whistling heard in telephone wires; umbrellas used with difficulty
7	Moderate gale	28	25-31	**12.4**	11.1-13.8	Whole trees in motion; inconvenience felt when walking against wind
8	Gale	34	31-38	**15.1**	13.8-16.9	Breaks twigs of trees; generally impedes progress

Table 5. Roughness parameters for wall boundary conditions.

	Aerodynamic roughness length z_0 (m)	Roughness constant C_s	Sand-grain roughness height k_S (m)
Building surfaces	-	0.5	0.10
Streets	0.02	2	0.10
Grass	0.03	3	0.10
Upstream domain area	0.11	7	0.15

FIGURE CAPTIONS



Ath	8.2 m	Fontys	15.2 m	LvA	7.4 m	PT	54.8 m	TWE	33.2 m
AUD	16.2 m	HAL	11.2 m	LG	7.5 m	SB	9.4 m	VRT	54.8 m
BBC	5 m	HE	24.1 m	MA	11.3 m	SPE	15.2 m	WF	3 m
CC	19.4 m	HG	45.4 m	MAC	5.3 m	SP	12 m	Wh	9.5 m
CR	12.3 m	IM	9.1 m	MMP	9.4 m	TNO	23.8 m	WH	18.2 m
CYC	8.5 m	IPO	15.2 m	NL	12 m	TR	15.2 m	WL	10.1 m
H2, H3, H4	5 m	KP	29 m	PAV	5 m	PAV-NP	3.5 m	ZD	12 m

Figure 1. Overview of buildings at the campus of Eindhoven University of Technology (TU/e). For every building, its abbreviated name and the average building height are indicated.

Figure 2. Photograph of (a) high-rise HG building with characteristic through-passages at both ends and (b) high-rise PT building.

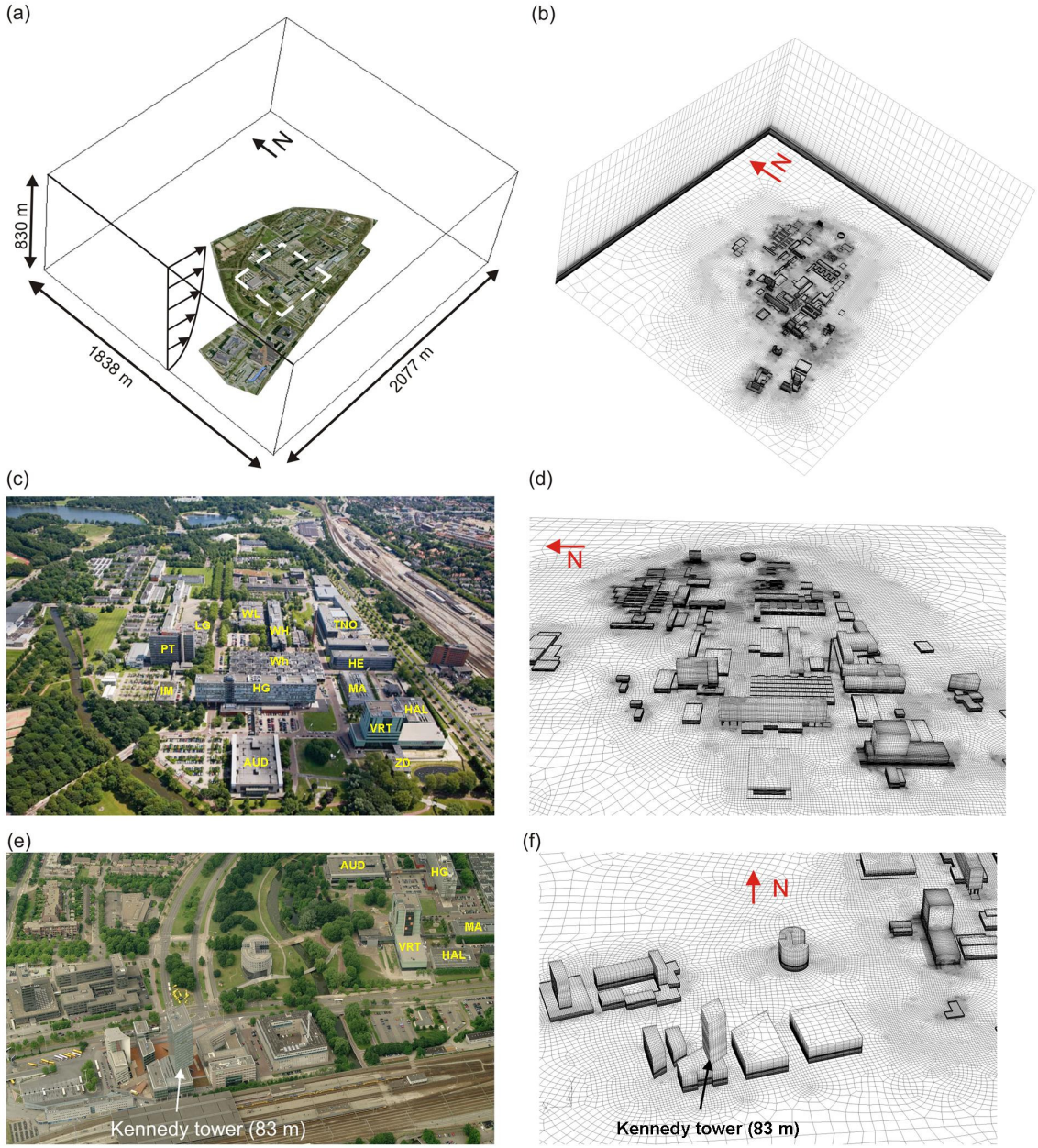


Figure 3. (a) Computational domain with aerial photo of the explicitly modelled buildings; the area of interest is indicated by the dashed rectangle. (b) Corresponding computational grid on the building surfaces, ground surface and two side faces of the domain. (c) Photo of the TU/e campus terrain, taken from west, with indication of abbreviated building names. (d) Corresponding high-resolution computational grid (7.554.091 cells). (e) Photo of part of campus and of several buildings off the campus terrain; view from south. (f) Corresponding high-resolution computational grid.

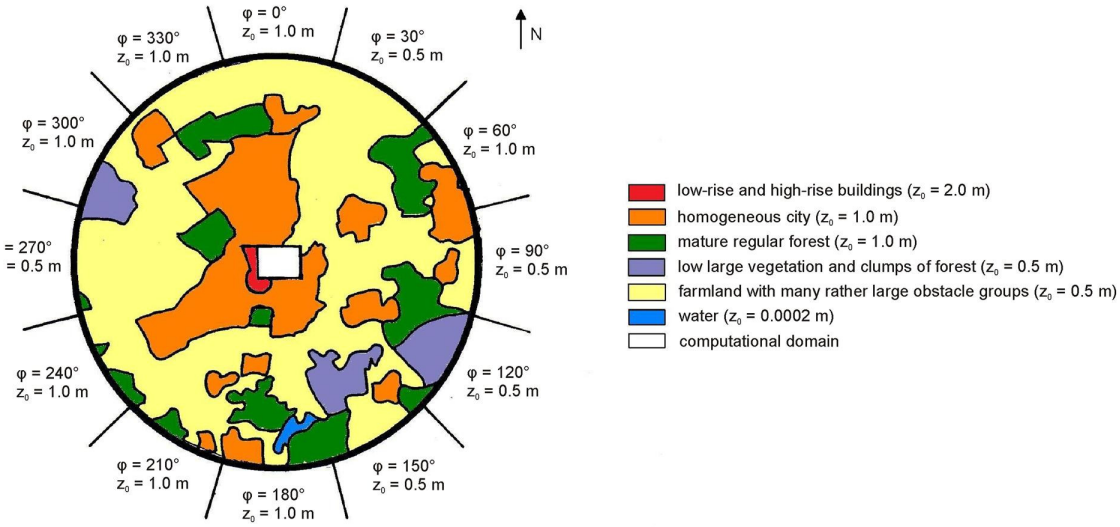


Figure 4. Surroundings of the university campus domain in a 10 km radius, with indication of the aerodynamic roughness length z_0 according to the Davenport-Wieringa roughness classification.

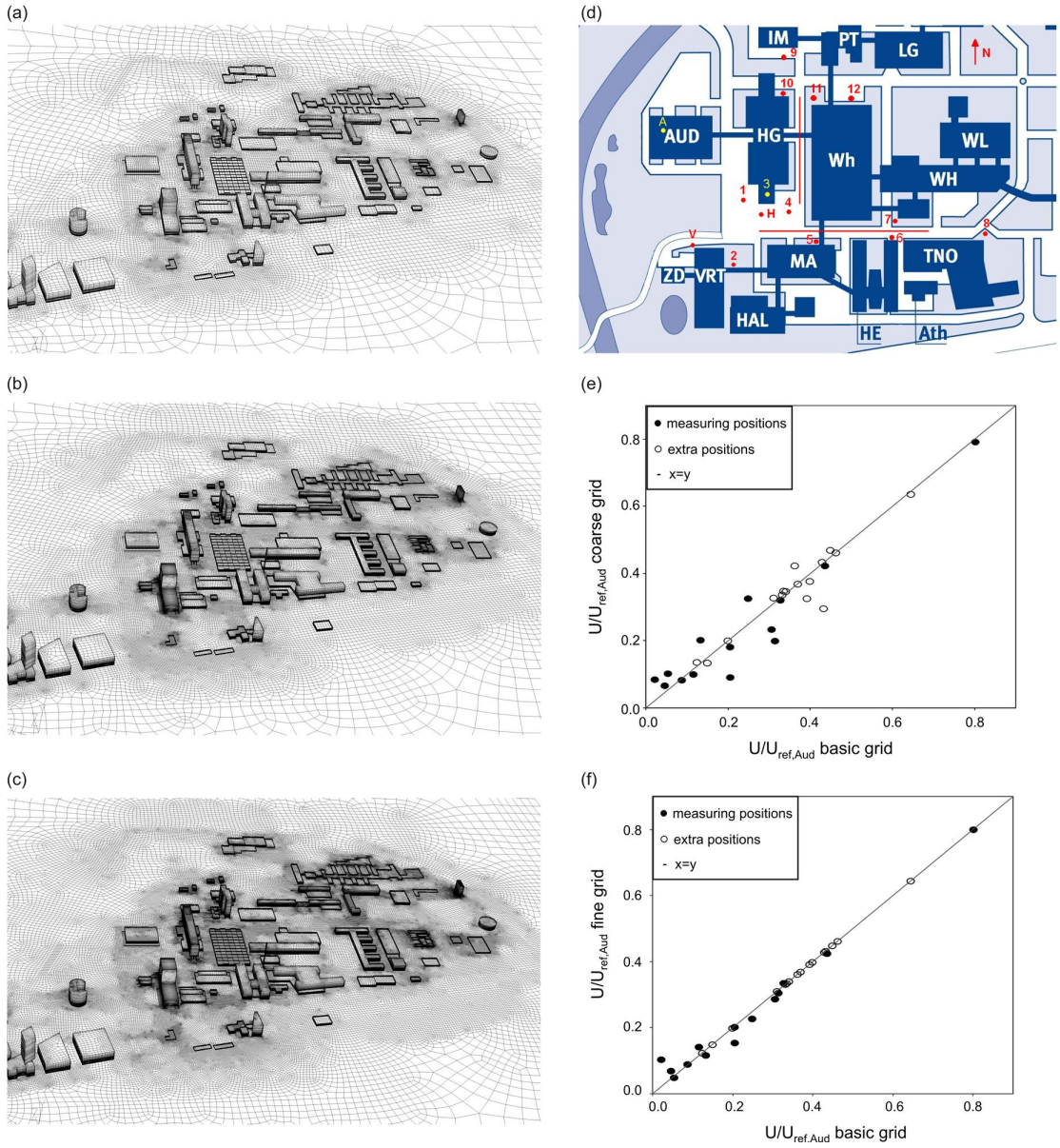


Figure 5. Grid-sensitivity analysis for comparison of mean wind speed ratios ($K = U/U_{ref,Aud}$) for $\varphi = 215°$ at different positions. The reference position is on top of a mast on the Auditorium Building (AUD) at 44.6 m height. (a) Coarse grid with 2,598,602 cells. (b) Basic grid with 7,554,091 cells. (c) Fine grid with 12,392,255 cells. (d) Positions for grid-sensitivity analysis. (e) Comparison of mean wind speed ratios between coarse grid and basic grid. (f) Same, but for basic grid and fine grid.

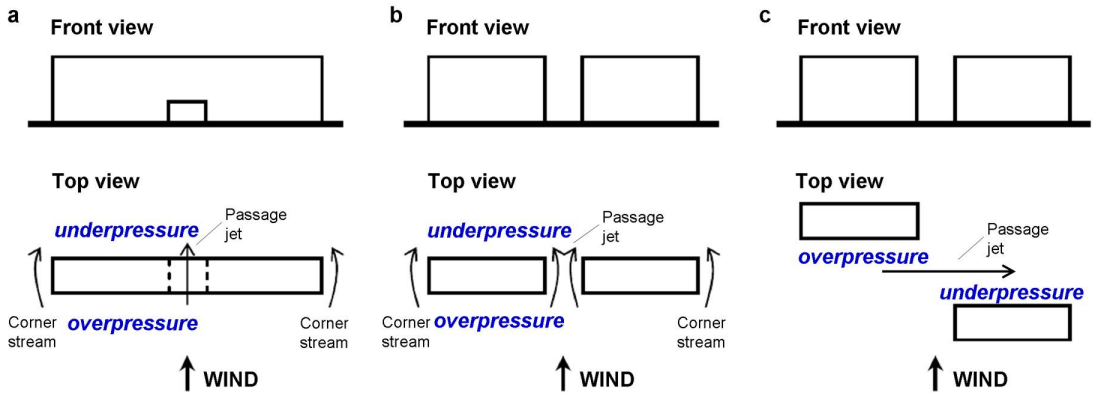


Figure 6. Schematic representation of building configurations prone to pedestrian-level wind nuisance: (a) through-passage in a building; (b) passage between two parallel buildings; (c) passage between two parallel shifted buildings.

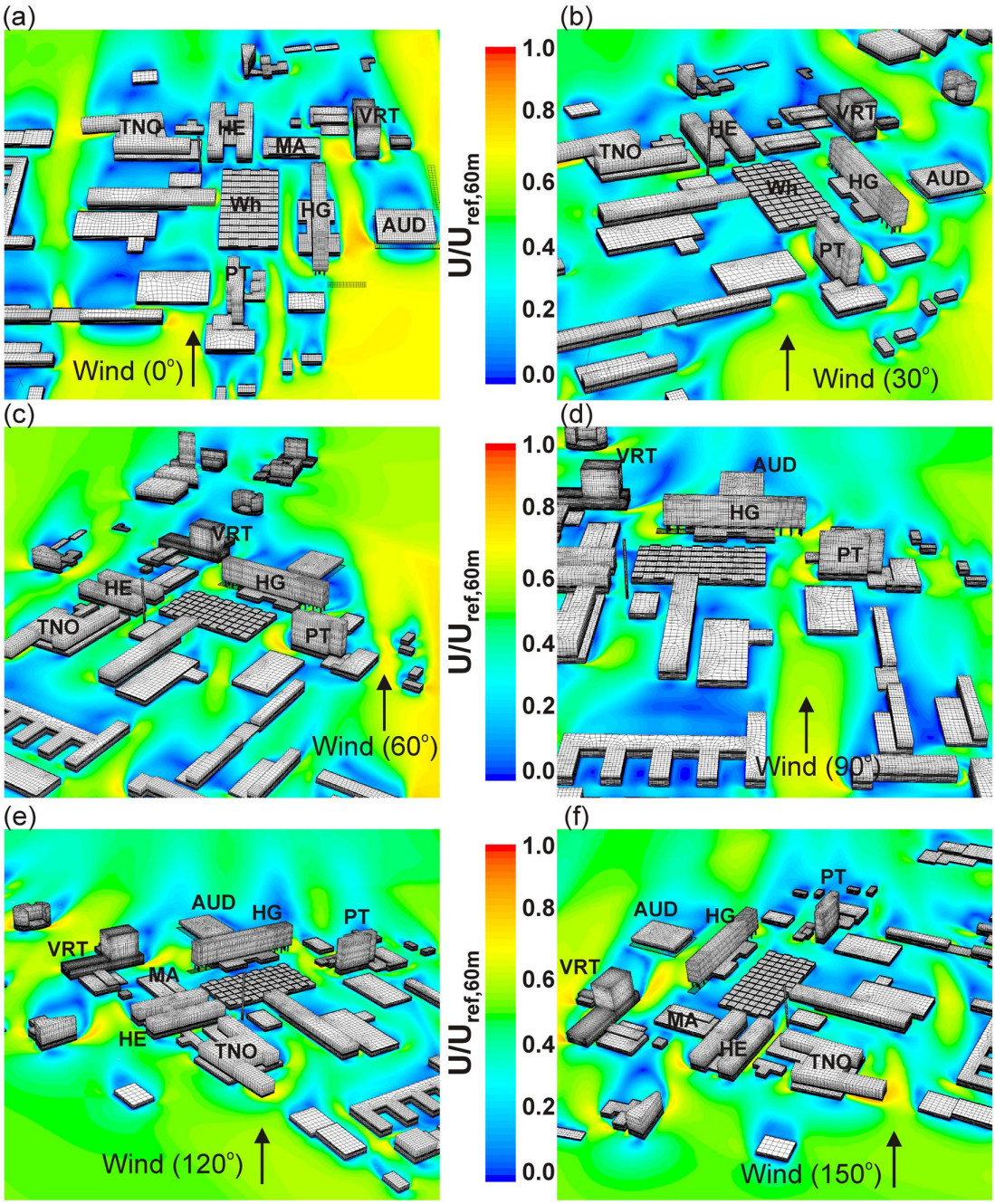


Figure 7. Contours of pedestrian-level (z = 1.75 m) wind speed ratio $U/U_{ref,60m}$ for six reference wind directions: (a) φ = 0°; (b) φ = 30°; (c) φ = 60°; (d) φ = 90°; (e) φ = 120°; (f) φ = 150°.

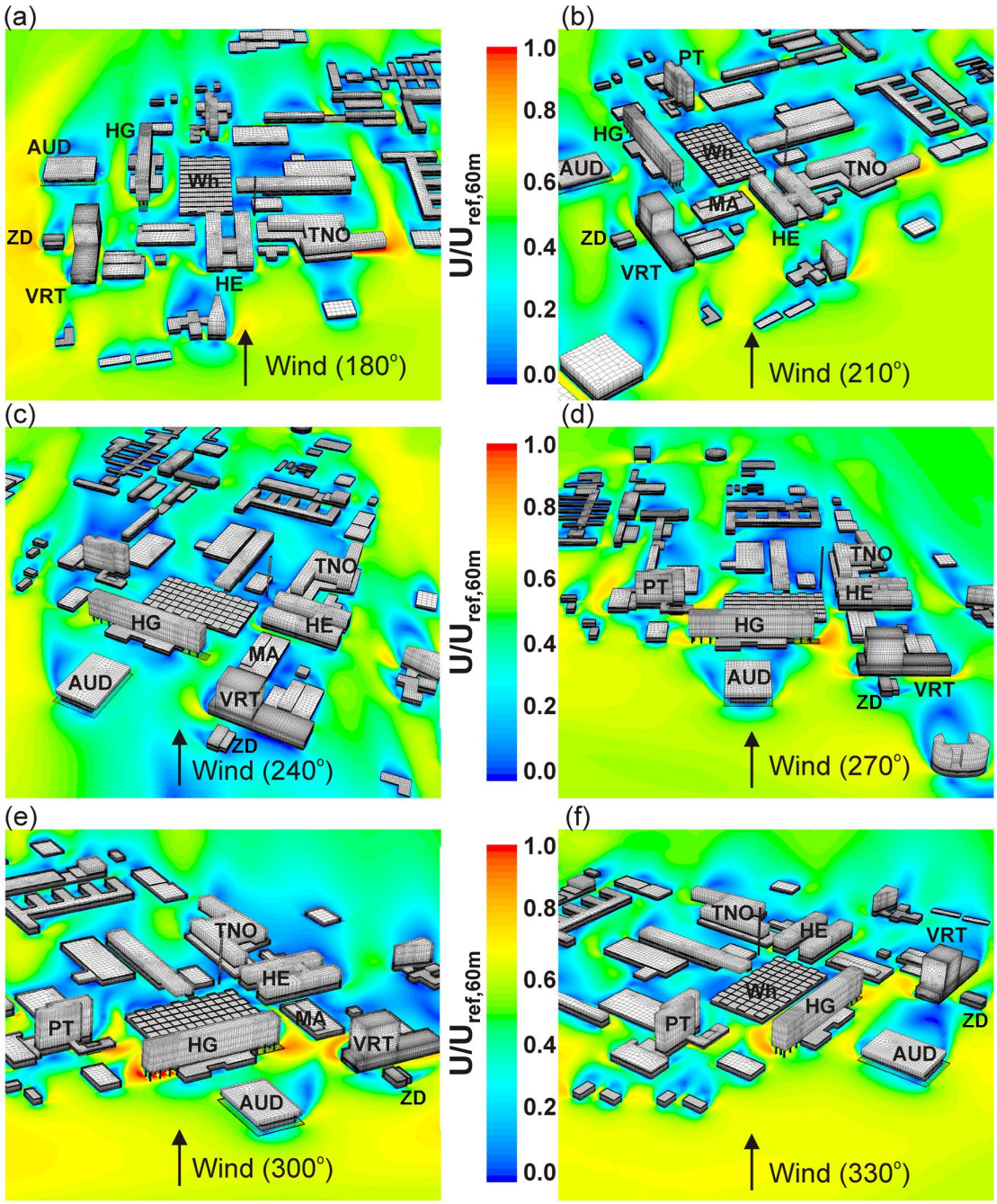


Figure 8. Contours of pedestrian-level (z = 1.75 m) wind speed ratio $U/U_{ref,60m}$ for six reference wind directions: (a) φ = 180°; (b) φ = 210°; (c) φ = 240°; (d) φ = 270°; (e) φ = 300°; (f) φ = 330°.

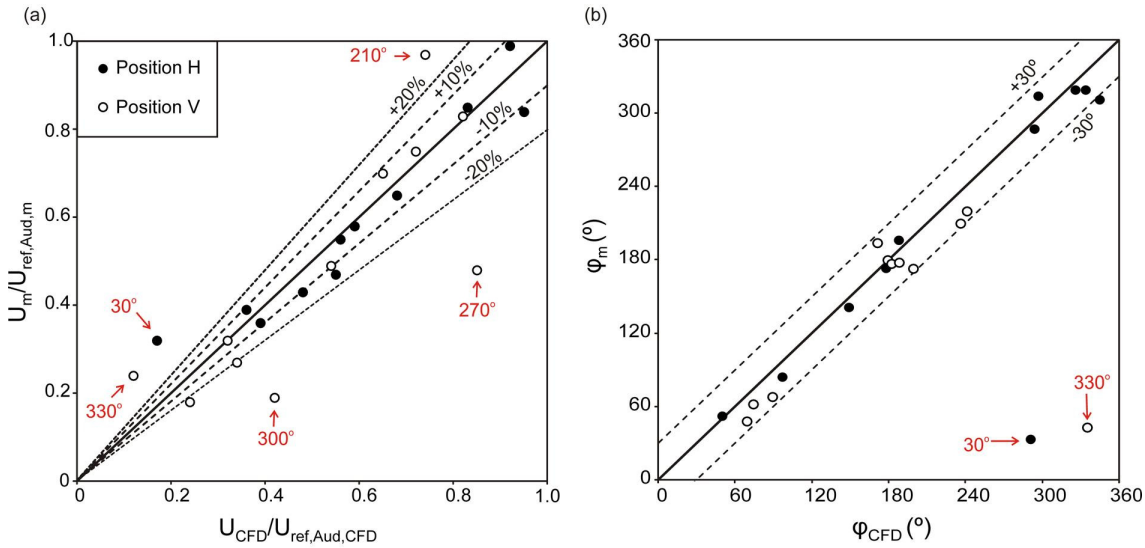


Figure 9. Comparison of CFD simulations and on-site measurements at the positions H and V shown in Fig. 5d in terms of (a) mean wind speed ratios $U/U_{ref,AUD}$ and (b) local wind directions φ. For the data points that show a large deviation between CFD and measurements, the corresponding reference wind direction is indicated.

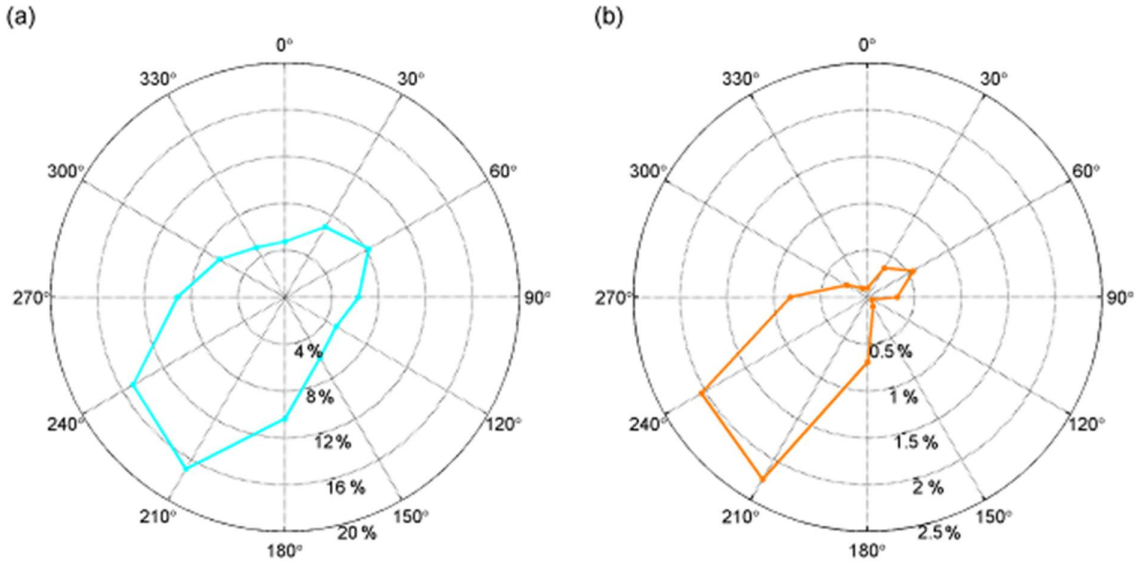


Figure 10. Wind roses for Eindhoven University campus, as obtained from the Dutch Practice Guideline NPR 6097. (a) Standard wind rose with frequency distribution of the hourly mean wind speed. (b) Wind rose with exceedance probability of the 5 m/s threshold at pedestrian height of 1.75 m, based on virtual open field conditions with z_0 = 0.03 m.

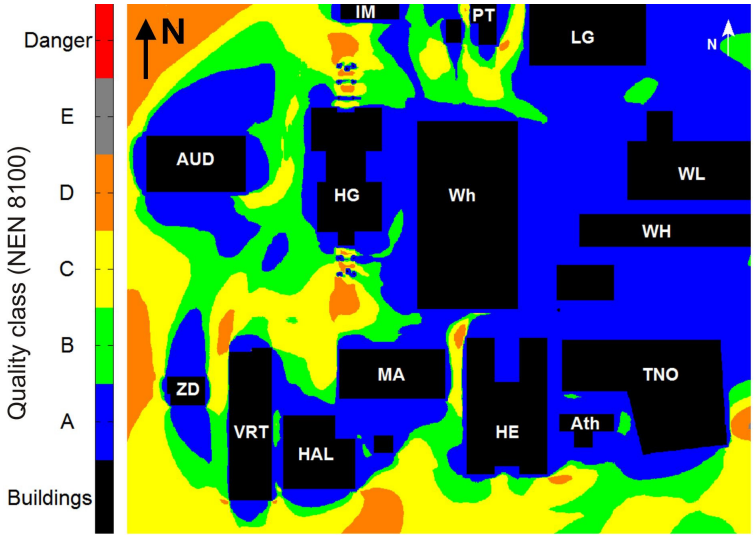


Figure 11. Assessment results for pedestrian wind comfort and wind danger (quality classes – see Table 1) according to the Dutch wind nuisance standard NEN8100.

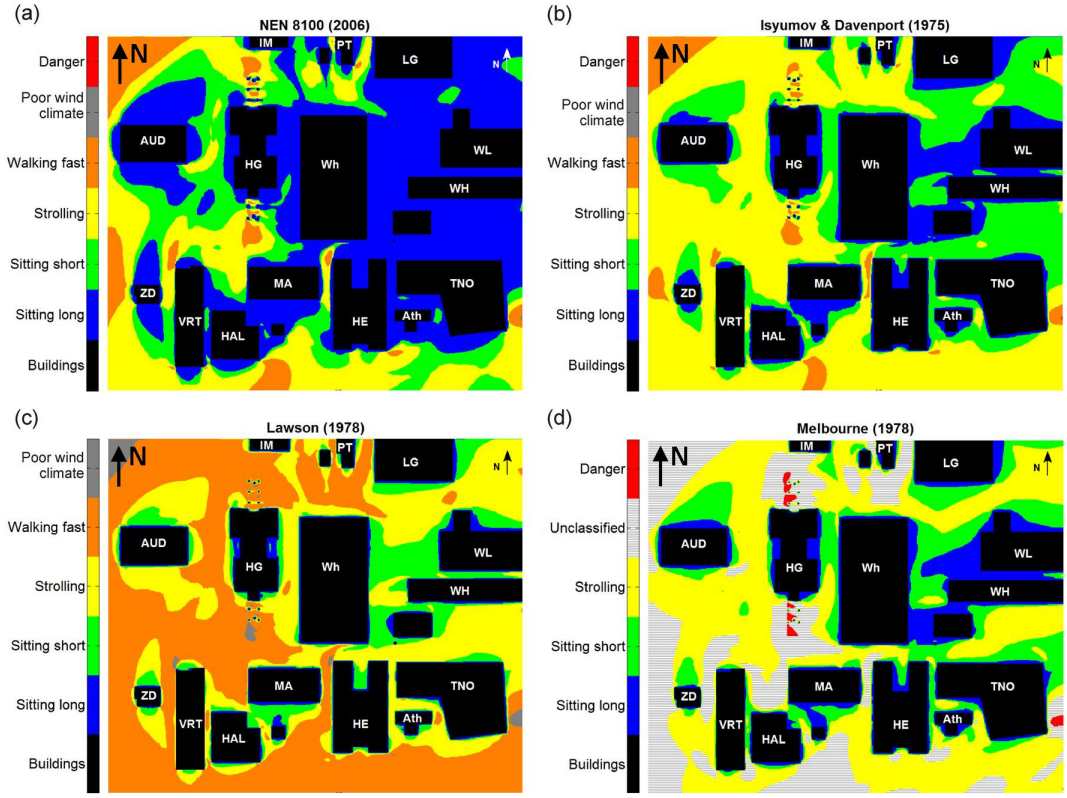


Figure 12. Assessment results for pedestrian wind comfort (moderate/tolerable wind climate for different pedestrian activities) and wind danger according to four different criteria: (a) NEN8100 (2006a); (b) Isyumov & Davenport [7]; (c) Lawson [8]; (d) Melbourne [1].