Towards wind modelling for sustainable building/urban design

Citation for the original published paper (version of record):

Pietrzyk, K. (2020). Towards wind modelling for sustainable building/urban design. IOP Conference Series: Earth and Environmental Science, 588(3). http://dx.doi.org/10.1088/1755-1315/588/3/032010

(article starts on next page)

IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Towards wind modelling for sustainable building/urban design

To cite this article: Krystyna Pietrzyk 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **588** 032010

IOP Conf. Series: Earth and Environmental Science **588** (2020) 032010 doi:10.1088/1755-1315/588/3/032010

Towards wind modelling for sustainable building/urban design

Krystyna Pietrzyk

Division of Building Design, Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins gata 6, SE412-96 Gothenburg, Sweden

Abstract. In view of climate change and resource depletion the analysis of wind impact on built environment could be used for conscious building/urban design protecting humans against high winds but also taking advantage of wind forces in terms of ventilation of spaces or production of wind-driven energy. There is a strong need of developing the modelling technology that would enable predictive studies in this field. Climate change mitigation and adaptation became the point of departure to introduce the notions of risk/chance analysis that could help to examine the architectural/urban design from the holistic perspective. The need of addressing different parts of wind velocity spectrum is acknowledged. The steps forming the process of design for sustainable wind environment are listed. Both the necessary test activities, and the simulation ones, as well as, the ones leading to the application of risk/chance assessment are discussed. Wind thresholds referring to different aspects, levels and scales of studies should be examined. They constitute the boundary of the uncertain set of expected acceptable solutions. In some cases, probabilistic model of thresholds could be considered. Joint project within the Digital Twin Cities Centre (DTCC) at Chalmers is referenced, where the newly established Vinnova Centre of Competence could offer the platform for the development of new modelling technology.

1. Introduction

In view of climate change and resource depletion the analysis of wind impact on built environment could be used for conscious building/urban design protecting humans against high winds but also taking advantage of wind forces in terms of ventilation of spaces or production of wind-driven energy.

Proper building/urban design must ensure structural stability and wellbeing of people both indoors and outdoors. Climate is the important factor (see figure 1). The actual wind condition is a result of wind interaction with all sorts of obstacles, also building structures (see figure 2). It is dependent on the wind speed and direction for various levels above the ground and the shape of obstacles (architectural form, physical plan), theirs air tightness (or permeability) and location in relation to adjacent buildings (urban plan). Modification of wind speed in the space between buildings can be achieved by choosing a proper location in relation to the natural morphology of the terrain, by conscious designing of a building shape, arrangement of adjacent buildings, and windbreaks.

The important issue is, which predictive models and tools are available to support building/urban design. Researchers at Chalmers within the DTCC [1] are working on wind simulations and visualization based on the fluid solver developed by Fraunhofer-Chalmers Research Centre, IBOFlow [2,3]. The work has become the part of the Centre's platform a big project aiming to analyse/communicate/visualize tangible and intangible city layers and flows. Starting from raw cadastre data [4], the ongoing research and development work follows the application needs and tries to respond to the research challenges, both on the district and the city level. Part of the plethora applications envisioned/planned by the Centre is wind simulations for sustainable building design and urban planning.

2. Risk/chance perspective on climate change mitigation and climate change adaptation

According to many sources climate change threatens life on our planet. In view of high uncertainty qualitative or semi-quantitative risk analysis based on the different scenarios is often applied and the needs for the reduction of the risk of climate change are formulated. Risk describes a state of uncertainty where some possible outcomes have an undesired effect or cause significant loss [5]. Following the quantitative definition of risk, it can be expressed–in terms of adverse consequences scaled by the probabilities of undesired outcomes:

$$Risk = P[hazard] * Consequences \quad (1)$$

$P[hazard]$ is the probability of occurrence of undesired events leading to possible $Consequences$ characterised by loss, injury, and discomfort.

Risk reduction could be accomplished by decreasing the probability of undesired event as well as diminishing the scale of adverse consequences. Risk reduction of climate change and its consequences can be accomplished by climate change mitigation (decrease of the probability of climate change) or climate change adaptation (decrease of the adverse consequences of climate change). The following definitions have been applied:

- Climate change mitigation – 'it consists of actions to limit the magnitude and/or rate of long-term climate change [6]. It generally involves reductions in human (anthropogenic) emissions of greenhouse gases' [7].
- Climate change adaptation – 'anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause or taking advantage of opportunities that may arise' [8].

Within the concept of climate change adaptation, the opportunities created by the climate change that may arise for some parts of the system could be acknowledged. Then, concept of Chance is introduced as a state of uncertainty where some possible outcomes have a desired effect or significant gain. It can be expressed in terms of positive consequences scaled by the probabilities of desired outcomes. It means that chance could be analysed in terms of the risk of positive/desired outcomes. Building/urban design for sustainable development can be approached using risk analysis tools. To minimalize the risk of undesired consequences while increasing the chance to enhance the quality of life becomes the basic design objective.

Climate adaptation of buildings/cities in the context of comfort and safety but also of low-energy operation can be evaluated from the perspective of sustainable development goals. It responds to at least 3 of them as listed by United Nations. There are: goal 7 – affordable and clean energy, and goal 3 – good health and well-being. Goal 13 – climate action is realized by climate change mitigation as "energy is the dominant contributor to climate change, accounting for around 60% of the global greenhouse gas emissions". Designing for the integration of the building form and structure with its external environment in order to use natural forces to secure comfort (passive strategies) is an example of activities towards mitigation of climate change. If it is supported by prediction of a local climate it can be viewed from the climate adaptation perspective too.

3. Risk assessment as a tool supporting design of buildings

Evaluation of building performance under uncertain wind conditions could be a tool to negotiate the final (re)design of buildings considering many performance aspects (see table 1), that are influenced by wind. The method for the quantification of building performance in terms of probability of poor

IOP Conf. Series: Earth and Environmental Science **588** (2020) 032010 doi:10.1088/1755-1315/588/3/032010

performance (failure) and probability of satisfactory performance is presented in [9,10]. Probability is treated as a measure of uncertainty about future events. Probability of a certain performance of a building/environment system depends on the theoretical model used and the variability of the influencing parameters. The epistemic uncertainty about the models applied together with the aleatory uncertainty coupled to the randomness of important phenomena contribute to the outcome. The needs for risk reduction related to the hazards introduced by climate change becomes an important boundary condition in the modelling of building/environment system to support building design. Following the definition of risk described by equation (1), adverse consequences could be presented in terms of money, number of affected people etc. If they are only indicated as existing or not existing {yes=1, no=0}, the probability P(hazard) becomes the discriminating factor for comparison of different design solutions [10]. It means that certain design could be chosen based on the comparison of probability of unsatisfactory performance or reliability, approximated for a set of alternative design proposals.

Figure 1 proposes a systemic perspective on building/environment performance. Designed object usually offers passive and active controls over the interior and outdoor climate. A passive control creates an extra climate-comfort loop [11]. Architectural interventions modifying air flow around and inside a building could be consciously introduced using holistic perspective on risk and chances supported by CFD simulations.

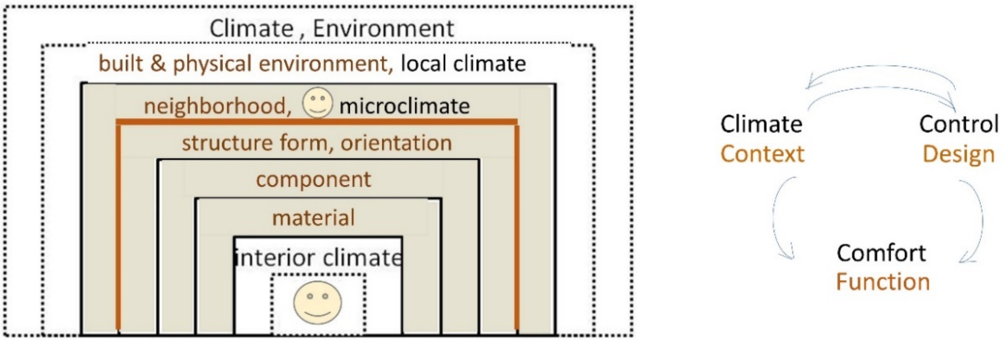


Figure 1. Comfort and safety in low-energy built environment – systems approach with focus on designing with wind (modified from [11]).

Climate adapted building or city provides comfort with the maximized contribution of the sun driven renewable energy sources. One of them is wind. Modification of wind speed in the space between buildings could be designed to minimize risk of pedestrian danger and discomfort caused by strong or polluted airflow, but also to take a chance of producing wind energy or designing for natural ventilation. The holistic view over risks and chances of the specific design followed by predictive modelling of wind properties in the city environment could support urban/building design. The risks and chances listed in table 1 are general ones and their pattern should be derived from the real case and context.

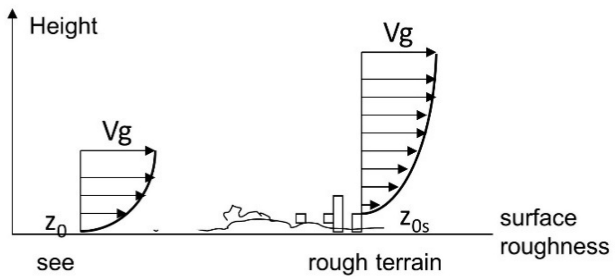
Table 1. The risks and the chances for designing with wind

Risks	Chances
wind-induced noise	pollutant dispersion around buildings
wind load or wind-induced vibrations	partial control of urban thermal environment
wind- driven rain on building facades	improving overall energy performance of buildings (passive/hybrid strategies)
extended heat losses through building facades	wind resource assessment for modelling of wind energy
pedestrian wind danger and discomfort	creating building performance for the outdoor environment (kinetic architecture etc.)
interior draughts	

Additionally, there is a tendency in Sweden to introduce more high-rise buildings. The effect of such changes in urban skyline on the wind conditions at the pedestrian level should be carefully studied. Urban aerodynamics seeks to help town planners and designers improve comfort in outdoor spaces, create urban microclimates and reduce the negative effects of wind on sustainability.

4. Properties of wind in built environment

Mean wind velocity profile close to the ground (interfacial layer) is governed by the pressure differences caused by the presence of buildings, vegetation and topography. The nature of obstacles regulates the level of turbulence. When the wind velocity is greater than 10m/s, the influence of surface friction is predominant in distorting and generating a turbulent flow [12]. The characteristics of wind may be described by studying the mean wind velocity profile and the intensity of turbulence present in the flow. For practical reason, the mean wind velocity profiles are constructed by assuming exponentially increasing velocity or simplified log laws.



Types of surface roughness	Height z_0 (m)
Calm open sea, water area	0.0001
Airport runway area	0.01
Farmland with open appearance	0.05
Many trees and bushes	0.2
Suburbs	0.5
City, forest	1.0

Figure 2. Velocity profiles over the smooth surface (see) and over the rough terrain, types of surface roughness.

Disturbance of the flow depends on the shape and height of the obstacles. Wind does not reach full speed (called gradient wind Vg) until a certain height off the ground; this height depends on the local obstructions and is referred to surface roughness. The roughness of the ground surface changes the mean wind speed and its turbulent characteristics and is described by the surface roughness height (aerodynamic roughness length) denoted z_0 (see figure 2). Roughness height depends on the mean element height of the roughness field. The results of laboratory measurements show that the value of z_0 is approximately equal to 1/30 of the height of the roughness elements. The surface roughness and obstacles usually decrease the wind speed but can also have speed up effect on wind. It happens when airflow is driven through a smaller cross section (for ex. passage through a building). It can also happen near to high rise buildings.

Horizontal wind-speed spectrum at Brookhaven National Laboratory at about 100-m height, $fS(f)$ against frequency f from Van der Hoven [13] is given in Figure 3. It describes the turbulent energy of wind over a frequency range. A big part is allocated in the atmospheric turbulence characterized by low frequency and large cycles. Atmospheric conditions and the building environment complicate the air flow. The separated flow on the roof and the leeward sides of the building is created by eddies of short duration. Their scale is less than that of the atmospheric turbulence (see figure 3). The spectral gap between the modes of spectrum - between 10 min. and 2 hours - indicates that the wind speed measured during this period can be regarded as steady. Therefore, for the common wind simulations 1-hour mean wind speed data, based on 10-min mean wind speed data measured at meteorological stations can be applied. High frequency turbulence generated by topography and structures is the main region of interest for dynamic response of wind turbines. Fluctuations of wind speed above the hourly average for certain turbulence intensity and the response time of the wind turbine can have negative effects on wind turbine performance. Wind energy spectrum could be also considered in the evaluation of wind-driven air exchange in buildings [14].

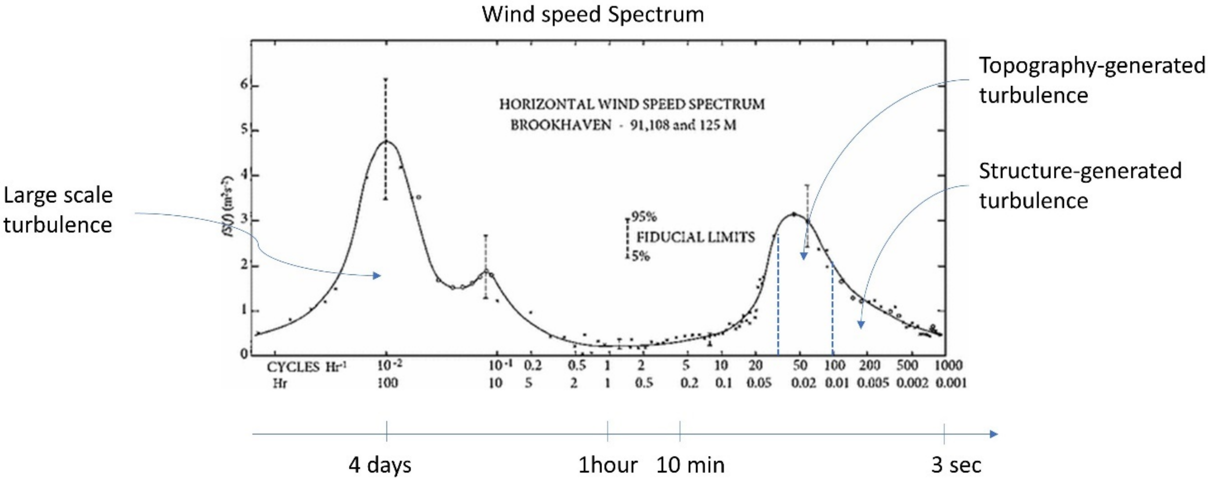


Figure 3. Wind energy spectrum. Wind turbulence atmospheric (large scale), topography generated, and structure generated (modified from [13,15]).

5. Wind modelling

Modelling of wind speeds in the vicinity of buildings was traditionally assisted by full-scale measurements and by wind tunnel tests. A serious problem with wind tunnel testing was related to the generation of atmospheric flow conditions. Nowadays, numerical simulations based on CFD are popular as a tool for supporting evaluation of airflow around buildings [16]. The solution provides the field distribution of air velocity and turbulence. Local wind speed at the boundary of the site investigated with the help of CFD simulations depends on climate and morphology of upstream terrain (aerodynamic surface roughness). Local wind modelling accounting for upstream terrain conditions includes surface roughness modelling in an atmospheric boundary layer [9,10].

Unfortunately, even in the case of CFD simulations the recreation of the atmospheric wind conditions with the proper velocity profile, velocity spectrum and spatial correlation is often neglected, and the simplified approach based on Reynolds-averaged Navier-Stokes simulations (RANS) with simple inlet conditions is used. Applying Large Eddy Simulation (LES) technique gives opportunity to account for the properties of atmospheric wind. LES provides deeper insight into unsteady flow phenomena. On the other hand, LES simulations are much more demanding in terms of computing resources. Many cases interesting to urban planning applications, still today seem to be beyond the reach of such simulations.

According to Blocken [16] RANS remains very popular in research applications, especially within areas of wind comfort, pollutant dispersion, urban thermal environment, natural ventilation and indoor airflow. Moreover, the capacity and performance of computer systems, as well as, the accessibility of powerful High-Performance Computing servers is constantly increasing. It allows for simulations of larger and more complex problems with RANS. Attempts of using LES to solve practical problems are also reported. Tolias et al [17] have studied the structure of the turbulent flow in the city area using LES. The velocity frequency distributions and energy spectra were evaluated. This kind of output is valuable for planning of location of the wind-power installations [18]. The results were compared to the scale experiment carried out in a wind tunnel. The simulations took several weeks per case, using hundreds of computers. Still, it is worth noting that such studies are beginning to appear in the literature.

Based on the simulation results of wind conditions in the urban area, the wind performance analysis for some aspects of sustainability could be carried out (see figure 4). The holistic analysis of risks and chances of wind modification in built environment would lead to setting up program of relevant simulations to prioritize the most effective solutions. Wind thresholds referring to different aspects, levels and scales of studies should be examined. They constitute the boundary of the uncertain set of expected acceptable solutions. In some cases, probabilistic model of thresholds could be considered [19,20]. Pedestrian wind comfort and safety is the most common issue to be analysed at the early stage of architectural/urban design process. Air infiltration and ventilation studies could be added, in order to investigate the feasibility of passive strategies.

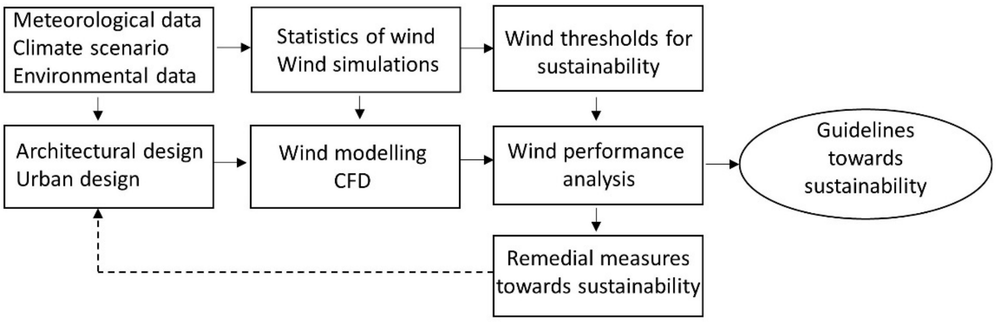


Figure 4. Wind in built environment for sustainable design.

The strategy for addressing the wind modelling could follow the outline below:

1. **Wind data processing** - synoptic wind, full-scale data for specific locations.

2. **Architectural design** – geometry, arrangements of buildings. Examples of urban solutions resulting in wind discomfort of pedestrians should be studied. The area of a building complex chosen for case study should be described as 3-D object in the database system.

3. **Wind field modelling**. Modelling of the local wind accounting for upstream terrain conditions. It includes derivation of statistical measures for local wind accounting for differences in surface roughness between the meteorological site and terrain surrounding the building complex [9]. Modelling of the airflow around the building complex - using CFD tools for various (including extreme) wind conditions. Validation data collected in full-scale measurements or laboratory scale models (wind tunnel) should be used to validate obtained results. Full-scale experimental data are to be preferred, due to the issues with recreating atmospheric turbulence in the scale experiments.

5. **Wind performance criteria** for sustainable development. Thresholds towards sustainability: e.g. against pedestrian discomfort, for wind safety etc., should be developed. For deterministic thresholds – analysis of the research results is sufficient. Thresholds for physical aspects of wind could be also determined using probabilistic approach because of uncertainty of human perception [11].

6. **Wind performance analysis**. The analysis of the performance of wind environment around the buildings in the selected aspects of sustainability should be carried out. It includes development of the model for quantification of a probability of undesired effects of air movement based on simulated wind field data and stochastic performance criterion. Risk analysis of undesired conditions caused by wind in urban environment should be carried out**.**

6. **Architectural remedial measures**. Modification of wind speed in the space between buildings can be achieved by choosing a proper location in relation to the natural morphology of the terrain, by conscious design of a building shape, arrangement of adjacent buildings, windbreaks, etc. Design of investigated building site should be improved in order to mitigate undesired consequences of winds based on comparison of the results obtained for different architectural and urban design, as well for different climate scenarios**.**

7. **Guidelines toward sustainability** should be developed from larger number of case studies. It could be understood as an interpretive interface based on the systems approach to design object as including broad environmental context, and risk/chance analysis of the chosen set of performance aspects.

The results of the simulations carried out within the DTCC platform can be aimed towards investigating sustainable solutions of building and urban design. Moreover, some other tools for climate assessment in built environment, e.g. analysis of solar radiation exposure of different surfaces should be integrated with the 3D system and coordinated in order to facilitate architectural/urban design responding to building/urban climatology [21]. Generally, urban physics issues, including wind could give a broader picture of factors influencing design process where environmental context would be put in centrum as one of the most important for form generation. Links between grand societal challenges and urban physics focus areas are presented in [22,23].

6. Conclusions

Sustainability issues should be discussed in relation to the environmental and climate conditions of the site both at the building scale and at the urban one. The modelling approach and the wind simulation tools should be consciously chosen according to their suitability to handle specific aspects of sustainable urban solutions. Eventually, a holistic approach to risk and chances of wind modification in the built environment should be applied in respect to different scenarios of climate change. Wind thresholds referring to different aspects, levels and scales of studies should be examined. They constitute the boundary of the uncertain set of expected acceptable solutions. In some cases, probabilistic model of thresholds could be considered.

Architects/urban planners could be much more effective in using the last decade's research results on wind energy and wind comfort and safety, for sustainable urban planning. Guidelines toward sustainability should be elaborated. It could be understood as an interpretive interface (wind simulations/design decision) based on systems approach and risk/chance analysis of the selected design in terms of chosen performance aspects. Guidelines should be developed from the larger number of case studies performed by other researchers as well as from the before mentioned activities within Chalmers University of Technology and DTCC. The Centre's platform CFD module is based on the Immersed Boundary Method powered by IBOFlow, running Reynolds Averaged Navier-Stokes (RANS) simulations with various turbulence and roughness models. The approach based on RANS could require refinement with more explicit turbulence modelling, especially when trying to resolve higher frequencies. Still, RANS could be applied for the chosen built environment and for different wind climate scenarios up to the extreme wind conditions. This could help to evaluate consequences of different designs in terms of climate change mitigation and adaptation. The knowledge gained through prospective case studies could be incorporated when developing new building codes/recommendations in view of climate change. Contribution of practicing architects and urban planners in above investigations is important, but it requires some basic understanding of fluid mechanics, computational techniques [16] and wind engineering.

Acknowledgments
The financial support provided by the Adlerbert's Foundation is gratefully acknowledged.

References

[1] https://www.chalmers.se/en/departments/ace/news/Pages/Digital-Twins-will-revolutionise-urban-development.aspx
[2] http://www.iboflow.com
[3] Mark A, Rundqvist R, Edelvik F 2011 Comparison between different immersed boundary conditions for simulation of complex fluid flows. *Fluid dynamics & materials processing* 7(3) 241-258
[4] Naserentin V, Logg A 2020 Efficient and robust 2.5D mesh generation for large-scale city modeling and simulation. Manuscript in preparation
[5] Bedford T, Cooke R 2001 *Probabilistic risk analysis. Foundations and Methods*. United Kingdom: Cambridge University Press
[6] Fisher BS et al. 2007 Ch. 3: *Issues related to mitigation in the long-term context*. In: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4WG3) (3.5 interaction between mitigation and adaptation, in the light of climate change impacts and decision-making under long-term uncertainty)

[7] *IPCC 2007 Summary for policymakers. Climate Change 2007*: Working Group III: Mitigation of Climate Change, Table SPM.3, C. Mitigation in the Short and Medium Term (until 2030) (IPCC AR4WG3)

[8] Climate Action. European Commission https://ec.europa.eu/clima/policies/adaptation_en

[9] Pietrzyk K 2000 *Probabilistic modelling of air infiltration and heat loss in low-rise buildings.* Ph.D. thesis in Building Technology/Building Physics, School of Architecture, Chalmers University of Technology, Sweden

[10] Pietrzyk K, Czmoch I 2018 On Risk and Reliability Studies of Climate-Related Building Performance, *Risk Assessment*, Valentina Svalova, IntechOpen,

[11] Pietrzyk K 2018 Bioclimatic tools for sustainable design – uncertainty perspective. Proceedings of the *7th International Building Physics Conference IBPC18 Healthy, Intelligent and Resilient Buildings and Urban Environments*, Syracuse USA, 511-516

[12] Handa K 1996 Turbulence characteristics and wind energy spectra. *Repor*t. Architecture, Chalmers University of Technology.

[13] Van der Hoven I 1957 Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. *J Meteorol* 14:160–164

[14] Pietrzyk K 2020 Analysis of wind speed and wind pressure on the facades in frequency domain for the modelling of air change rate. Manuscript accepted for the Proceedings of the Nordic Symposium on Building Physics NSB2020

[15] Gustén J 1989 *Wind pressures on low-rise buildings*. Ph.D. thesis, Chalmers University of Technology, Sweden

[16] Blocken B 2018 LES over RANS in building simulation for outdoor and indoor applications: A forgone conclusion? *Build Simul* 11: 821-870

[17] Tolias L C, Koutsourakis N, Hertwig D, Efthimiou G C, Venetsanos A G, Bartzis J G, 2018 Large Eddy Simulation study on the structure of turbulent flow in a complex city. Journal of Wind Engineering & Industrial Aerodynamics 177 101-116

[18] Soberanis M A, Mérida W 2015 Regarding the influence of the Van der Hoven spectrum on wind energy applications in the meteorological mesoscale and microscale. *Renewable Energy* 81 286-292

[19] Pietrzyk K 2015 A systemic approach to moisture problems in buildings for mould safety modelling. *Building and Environment* 86 50-60

[20] Pietrzyk K, Hagentoft C.-E. 2008 Reliability analysis in building physics design. *Building and Environment* 43/4 558-568

[21] Wong N H, Jusuf S K, Tan C L 2011 Integrated urban microclimate assessment method as a sustainable urban development and urban design tool. *Landscape and Urban Planning* 100 386-389

[22] Toparlar Y, Blocken B, Maiheu B, van Heijst G J F 2017 A review on the CFD analysis of urban microclimate. *Renewable and Sustainable Energy Reviews* 80 1613–1640

[23] Blocken B 2015 Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Building and Environment* 91 219-245