Leveraging Urban Configurations for Achieving Wind Comfort in Cities

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Abstract. Given the continuous improvements in digital design and analysis tools, designing in line with the environmental conditions can be much more seamlessly integrated into the conceptual design stage. That leads to faster, informed design decisions and, if incorporated into day-to-day practice, to a sustainable built environment. The presented design method, focusing on enhancing the outdoor wind comfort through architecture, leverages wind analysis tools, such as newly-developed InFraRed, verified by other Grasshopper plug-ins, in the urban design process. As shown in the case study, iterating through various design options and evaluating their impact on the wind flow is faster yet precise, leading towards picking the best-performing design alternative in terms of outdoor wind comfort.

Keywords: Real-time wind predictions, Wind comfort, Parametric design, CFD analysis, Machine learning, InFraRed

1 Introduction

Architectural design is a complex process, where various inputs and criteria of different importance are involved in design creation. The impact of environmental parameters on architecture, among influences affecting design decisions, started to be considered more in the early design stages, with the advancements of digital design tools and architectural computing (Kuenstle, 2002); (Pellitteri et al., 2009); (Wang et al., 2016). For instance, the effects of the wind flow around buildings of varying heights, shapes, or mutual distance, if not considered during the design, can result in unpleasant, uninhabitable urban spaces (Szücs, 2013); (Janssen et al., 2014). Computational Fluid

Dynamics (CFD) simulations, which predict complex, buildings vs. wind flow interactions, are gradually integrated into the architectural design (Chung & Choo, 2010); (Valger & Fedorova, 2020); (Duering et al., 2020), enabling to make informed, environment-based design choices. However, although the integration of CFD analysis in the early design stage has clear benefits, there still are obstacles to its everyday use, such as the required expertise in the field, the computational time needed for the analysis, or the price of the essential hardware and software.

The paper focuses on the future of sustainable city planning and designing with the wind flow as one of the crucial design factors. The objective of this study is, through a case study, and incorporating fast wind analysis tools, to develop and test a top-down approach to designing architecture, which can, through its shape, utilize the favorable or reduce unfavorable wind effects. This approach not only enables faster environment-based decision-making in the complex process of urban and architectural designing but also leads to improvements in the local ambient conditions.

2 Methodology

With the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) underway, the importance of limiting global warming to 1.5 °C is stressed, and the mitigation or adaptation scenarios are investigated (IPCC 6, 2018). Architectural engineering may contribute to the climate change adaptation efforts and help mitigate extreme weather events and create a pleasant climate in urban areas through climate-related planning in the early design phase (Dubois et al., 2015).

As is shown in this paper, the unfavorable wind effects, such as accelerated wind or turbulence created by the urban configuration, can be identified and addressed throughout the design process. Moreover, passive air exchange will be leveraged to achieve natural ventilation in outdoor spaces (Sangdeh & Nasrollahi, 2020). Directing the airflow could not only contribute to dispersing pollutants (Valger & Fedorova, 2020), but also to reducing the urban heat island effect, i.e., the overheating of urban areas (Dubois et al., 2015).

2.1 2.5 x 2.5 km zone

A mixture of techniques is used, including InFraRed, a machine learning (ML) wind-prediction tool developed by the AIT’s City Intelligence Lab (Duering et al., 2020), and CFD plug-ins for Grasshopper (Rhino), specifically Butterfly, as well as Procedural Compute (both utilizing OpenFOAM) for verification of the fast ML analysis and the suitability of its use in the architectural/urban design process.

Kosice, a 250 thousand inhabitants city in eastern Slovakia, is picked as a case study site. An area of 2.5 x 2.5 km is selected, and the existing wind situation is analyzed employing the said tools. The simulations are performed for northerly winds, which are prevailing in Kosice (Figure 1). The wind data for Kosice are obtained from the EnergyPlus web database (EnergyPlus, 2021).

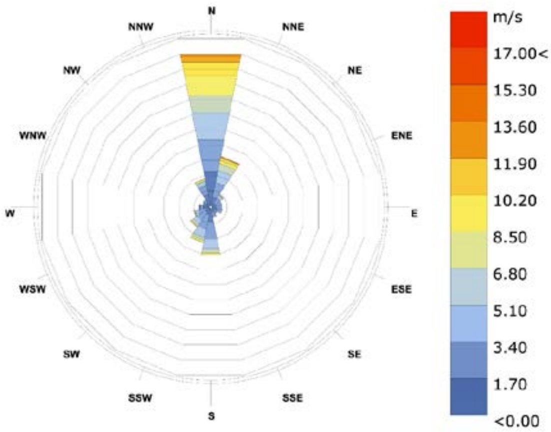

Figure 1. The wind rose for the city of Kosice, Slovakia, generated through Grasshopper - Ladybug. Northerly winds are prevailing 33.46% of the time, with speed > 5 m/s 12.87 % of the year.

Although the city of Kosice lies in a valley, the terrain is not considered in the wind simulations because InFraRed (Python-based ML model enabling quick wind analysis in Grasshopper) is not yet trained to work with terrain morphology. Therefore, the tested area is modeled on a flat surface in Rhino, using simple, closed mesh geometry. The height of the buildings is set using the bounding box around geometry to obtain the maximum elevation of each building.

To estimate the wind flow at the pedestrian level (1.75m above the ground), InFraRed is utilized uniquely. Given that InFraRed predicts wind flow at a 250 x 250 area, predicting wind comfort and flow values with InFraRed happens by convolving such a 250 x 250 m cell across the map, with a stride of 100 m. That allows for a more accurate prediction at the center of each location, considering the urban context around it, discounting the overlapping regions[1]. The input wind speed is 10 m/s, and the wind direction is 0° (northerly winds). The whole wind analysis process is executed in under 30 seconds. The wind prediction of the 250 x 250 m site would be performed instantly, nevertheless, we needed to analyze a more extensive zone, which required additional time.

Within the tested area, the zones with green-yellow-red colors (higher wind speeds) are marked (Figure 2), omitting the outskirts of the tested area. These cannot be accurately evaluated for lacking the context of neighboring buildings. The frames depicted in Figure 2 are 500 m long by 500 m wide. The output of the InFraRed wind prediction will be compared to the CFD simulations.

Later, we will focus on Zone 01, which will be studied in greater detail.

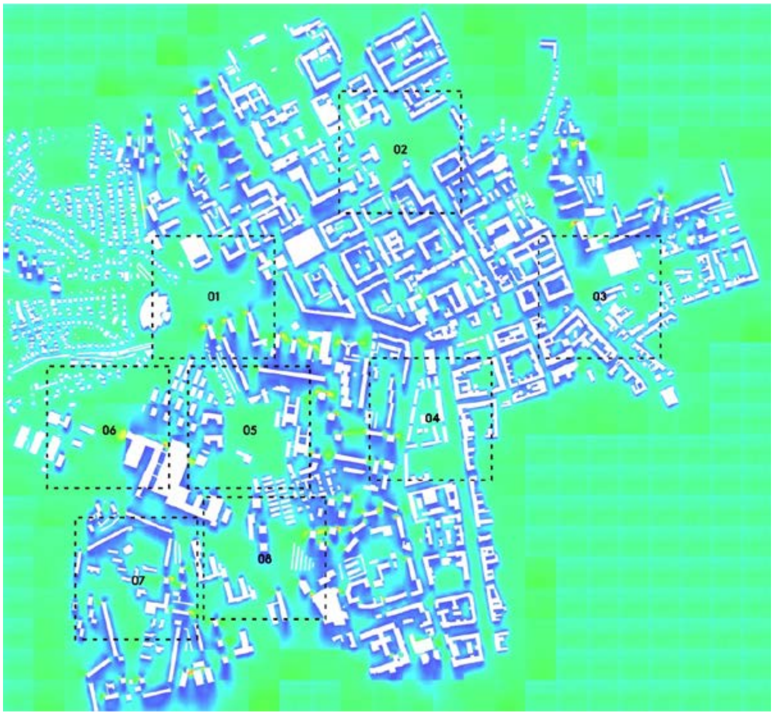

Figure 2. InFraRed wind speed prediction (blue color = 0 m/s, red color = 10 m/s).

The 2.5 x 2.5 km area is a computational burden for personal computers. Naturally, investigating such a large area using CFD simulations demands better computer parameters and a long run time.

Procedural Compute (Pitman & Kongsgaard, 2021) is an OpenFOAM-based plug-in for Grasshopper, which orchestrates building physics simulations in the cloud, hence not loading the local machine. The initial set-up is made through the Grasshopper plug-in from which the case is sent to the cloud server.

The large-scale 3D wind simulation of Kosice is run with the SimpleFoam solver for northerly winds with the input wind speed of 10 m/s and the settings from Table 1.

The simulation was stopped after 3200 iterations (after around 24 hours) without reaching convergence as the values of initial residuals were stabilized. The whole process, except the initial settings in Grasshopper, was performed online. For the post-processing of the results, the Paraview Web Visualizer was used.

Table 1. Procedural Compute CFD settings.

Setting	Specification
CPUs	24
Cell size	10 meters
No. of cells	15.98 million
Geometry	Meshing level 3
Geometry in the outskirts	Meshing level 2
No. of Nonorthogonal Correctors	1
Relaxation factors	p = 0.3 U = 0.7 k/ε = 0.7

The two wind analysis results (InFraRed and Procedural Compute) cannot be directly compared only visually, through colors.
However, we can identify wind flow acceleration, as well as turbulence in both outputs (zones in the dotted frames).

Although there are some discrepancies, for instance, the acceleration of the flow in Zone 10 is predicted only by the CFD, the results of the CFD calculations (Figure 3) show a very similar trend as was predicted with InFraRed.

Introducing the machine learning tool into the early design phase, the problematic areas where the wind flow accelerates or is turbulent are identified quickly. InFraRed, used for predicting the wind flow in the 2.5 x 2.5 km area, provides a quick and accurate understanding of the influences of buildings in this urban context on the air fluxes at the pedestrian level. OpenFOAM-based CFD simulation captures the flow downstream with more discernible areas of wind turbulence. Also, the complex mutual relations of the urban context influencing the wind flow are more precisely captured with the CFD, as InFraRed is only joining together smaller zones to create the large-scale analysis output.

2.2 500 x 500 m zone

The second step in our wind-based designing is to analyze one spot selected from the larger, previously investigated area in more detail. Zone 1 was prognosticated with both analysis tools to have large regions of accelerated wind between the existing buildings as well as turbulent wind downstream.

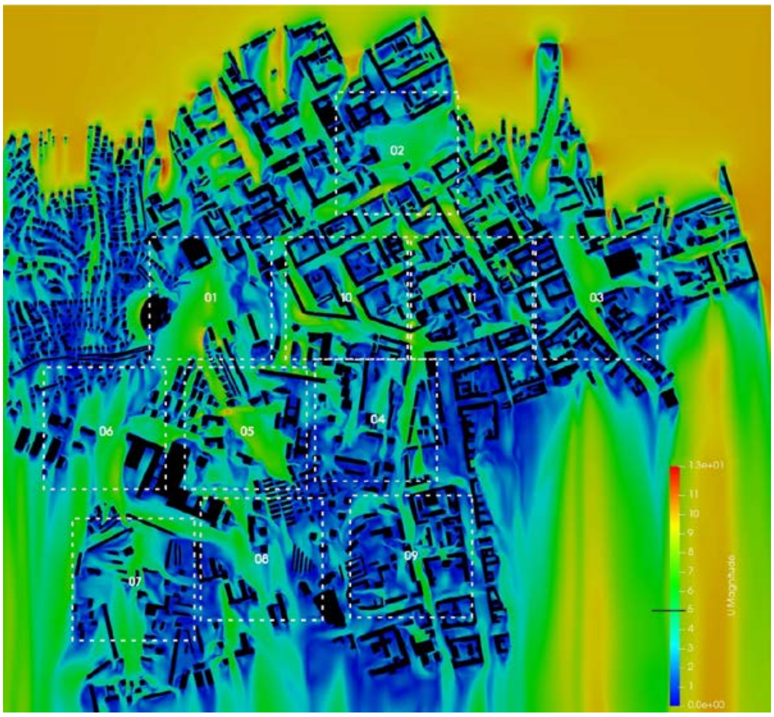

Figure 3. Procedural Compute result processed in Paraview Web Visualizer (blue color = 0 m/s, red color = 13 m/s).

We proceed analogously as with the larger zone. First, the area sized 500 x 500 meters is tested using InFraRed. Here, however, InFraRed is used for directly testing this area, omitting the convolving approach.

InFraRed predicts high wind speed (up to 10 m/s) on the corners of the apartment blocks on the south and large areas with a wind speed of 5 m/s and more (green color) throughout the analysis zone (Figure 4). A short Grasshopper script is utilized to convert the colors to the specific wind speed values.

The CFD analysis of the same area is performed in Butterfly for Grasshopper, which is based, similarly to Procedural Compute, on the OpenFOAM platform. The settings of the simulation are listed in Table 2. The analysis is run on a personal computer; therefore, the settings meet the options of the computer. The finite volume cell size is now reduced to 5 m, although the geometry meshing level decreases.

Table 2. Butterfly CFD settings.

Setting	Specification

CPUs	12
Cell size	5 meters
No. of cells	770 032
Geometry	Meshing level 2
Geometry in the outskirts	Meshing level 1
No. of Nonorthogonal Correctors	2
Relaxation factors	p = 0.3 U = 0.7 k = 0.5 ε = 0.7

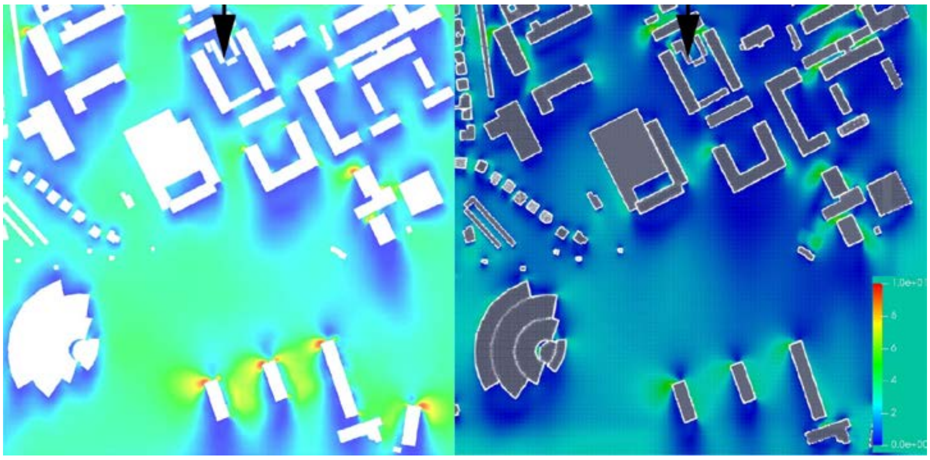

Figure 4. Left: InFraRed wind speed prediction of Zone 1 (blue color = 0 m/s, red color = 10 m/s). Right: The output of Butterfly CFD calculation (blue color = 0 m/s, red color = 10 m/s).

The turbulence model used for the calculations in Butterfly was Realizable k-ε. With the convergence criteria set to 1e^{-3}, the CFD simulation converged with the said settings in 850 iterations.

Figure 4 depicts the outcome of the CFD analysis. Here, the wind situation appears to be calmer than predicted with InFraRed. In the prevailing northerly winds, the acceleration manifests on the edges of the buildings. Turbulence forms around the roundabout because of the old printing factory's orientation (Figure 5) and its sharp geometry.

Figure 5. The map of the design site. Source of the map: Google Earth

2.3 Designing

Within the third step, an iterative process of designing and analyzing the design's wind performance takes place, leveraging a parametric design approach (Grasshopper) combined with the real-time wind analysis of the various urban design options (InFraRed). The wind flow control achieved through building shapes is the central design goal. The new design focuses on the area of the old printing factory (Figure 5). Instead of the old printing factory, apartment buildings with office spaces on the first floors will be designed.

We set two urban design goals in the wind-based planning: 1) public space in-between the designed buildings, which replace the old printing factory, should be comfortable for a prolonged outdoor stay (wind speed < 5 m/s, < 10% of the time) (Blocken et al., 2016), and 2) natural ventilation should be enabled between buildings, with the wind speed within the wind comfort limits.

InFraRed is employed to iterate through urban design options. The wind prediction is focused on the site of the old printing factory, which means that the analysis zone size is 250 x 250 m. Consequently, we use InfraRed without an additional need for creating a "stitched" image. Six design options are swiftly evaluated. The geometry is designed parametrically with the following variable parameters: 1) height (9 to 18 meters), and 2) the orientation angle (-15° to 15°). The footprint and the number of the buildings can be altered according to the ideas of the designer. Basic block geometries and simple cylinders represent buildings and trees, respectively. The purpose is to obtain a general idea of how their height and rotation towards the prevailing wind influence the wind flow.

3 Results

The performance of the six design options in the wind (Figure 6) is evaluated employing InFraRed. Specific wind speed values are examined through the previously mentioned Grasshopper script. Finally, option 3B is selected for the following reasons: 1) it does not create stagnant wind flow - the wind speed in between the buildings is 3-4 m/s, yet 2) it offers places with calm wind around the buildings – the speed around 1-2.5 m/s.

4 Conclusion

This study focused on the wind-based urban design approach, leading towards finding the best-fitting urban configuration in the presented context for further design elaboration. Incorporating ambient influences, such as the wind flow into the early phases of the design process, we can predict their impact on the future designs and the zones in their vicinity, and reciprocally, leverage building morphology for enhancing the quality of the environment, which gradually becomes the major player in the architectural design.

In the urban case study in Kosice, Slovakia, this iterative, wind-based designing, incorporating machine learning (ML) wind analysis tool InFraRed and two Grasshopper CFD plug-ins to verify the ML-based prediction, was introduced.

Fast wind-based optimization of the urban configuration in the early design phase (enhancements of outdoor wind comfort and a reduction of stagnant air in-between the newly planned buildings) enables rapid yet informed, environmentally-friendly design decisions in the architectural practice.

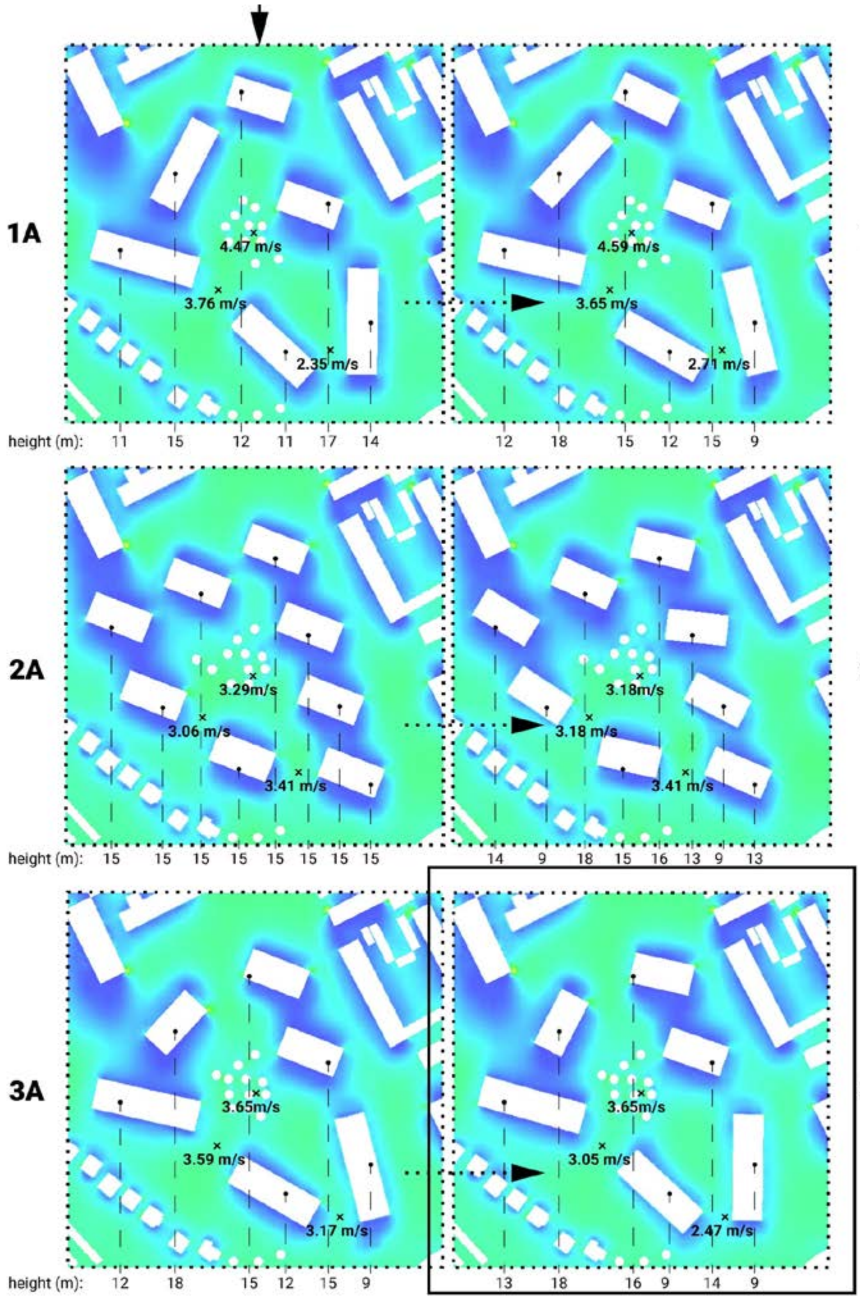

Figure 6. Six urban configurations of the planned buildings.

Nevertheless, InFraRed, while beneficial in this setting of understanding which areas might be relevant to focus on / or are problematic, it does not reach its full potential without big(ger)-scale explorations.

4.1 Fluid windcatchers

The eventual design will pick up on the wind-optimized urban configuration and introduce fluid architectural shapes into the concept. Their function as a windcatcher and a sun shading system will be examined and evaluated closely employing CFD Grasshopper plug-ins (Figure 7).

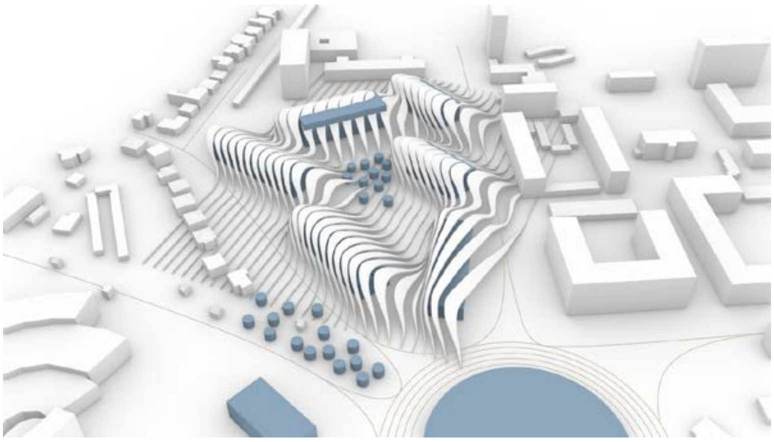

Figure 7. The idea of the further design of the case study site incorporating fluid architecture.

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[1] Courtesy of Narriddh Khean

References

Blocken, B., Stathopoulos, T., & van Beeck, J. P. A. J. (2016). Pedestrian-level wind conditions around buildings: Review of wind-tunnel and CFD techniques and their accuracy for wind comfort assessment. *Building and Environment*, *100*, 50–81. https://doi.org/10.1016/j.buildenv.2016.02.004

Chung, D. H. J., & Choo, M.-L. L. (2010). Computational Fluid Dynamics for urban design: The prospects for greater integration. *International Journal of Architectural Computing*, *09*(01), 33–53.

Dubois, C., Cloutier, G., Potvin, A., Adolphe, L., & Joerin, F. (2015). Design support tools to sustain climate change adaptation at the local level: A review and reflection on their suitability. *Frontiers of Architectural Research*, *4*(1), 1–11. https://doi.org/10.1016/j.foar.2014.12.002

Duering, S., Chronis, A., & Koenig, R. (2020). Optimizing Urban Systems : Integrated Optimization of Spatial Configurations. *SimAUD: Symposium on Simulation for Architecture & Urban Design*, 503–510.

EnergyPlus. (2021). *Weather data*. https://energyplus.net/weather

IPCC 6. (2018). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*. WMO Geneva.

Janssen, W. D., Blocken, B., & Van Hooff, T. (2014). Computational evaluation of pedestrian wind comfort and wind safety around a high-rise building in an urban area. In D. P. Ames, N. W. T. Quinn, & A. E. Rizzoli (Eds.), *Proceedings of the 7th Int. Congress on Env. Modelling and Software* (pp. 1–8). iEMSs.

Kuenstle, M. W. (2002). Flow structure environment simulation: A comparative analysis of wind flow phenomena and building structure interaction. In S. Koszewski, K. and Wrona (Ed.), *20th eCAADe Conference Proceedings* (pp. 564–568).

Pellitteri, G., Lattuca, R., Concialdi, S., Conti, G., & Amicis, R. De. (2009). Architectural shape generating through environmental forces. *Joining Languages, Cultures and Visions: Proceedings of the 13th International CAAD Futures Conference*, 875–886.

Pitman, M., & Kongsgaard, C. (2021). *Run your simulation in the cloud*. https://compute.procedural.build/

Sangdeh, P. K., & Nasrollahi, N. (2020). Windcatchers and their applications in contemporary architecture. *Energy and Built Environment*, *December*, 1–16. https://doi.org/10.1016/j.enbenv.2020.10.005

Szücs, Á. (2013). Wind comfort in a public urban space-Case study within Dublin Docklands. *Frontiers of Architectural Research*, *2*(1), 50–66. https://doi.org/10.1016/j.foar.2012.12.002

Valger, S. A., & Fedorova, N. N. (2020). CFD Methods in Architecture and City Planning. *Journal of Physics: Conference Series*, *1425*(1). https://doi.org/10.1088/1742-6596/1425/1/012124

Wang, L., Tang, Z., & Ji, G. (2016). Toward the wind-related building performative design. In S. Chien, S. Choo, M. A. Schnabel, W. Nakapan, M. J. Kim, & R. Roudavski (Eds.), *Living Systems and Micro-Utopias: Towards Continuous Designing Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA* (pp. 209–218).