Analysis of wind-adaptive architecture

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Abstract. As an architectural response to the changing climate, a wind-driven design approach is developed. By adopting the digital design tools, the wind can be integrated into the design process, from the large scale of urban planning, through the form-finding of buildings, as well as designing the texture and roughness of building surfaces. In its more extreme forms, it is even more notable, how the wind flow is shaped and influenced by architecture. Former docks in Stockholm serve as a case study site to test architectural interventions that alter the wind flow on the site. This wind-driven design approach enables the evaluation of the wind performance of various design options, which informs design decisions. Grasshopper, the graphical algorithmic plug-in for Rhinoceros, creates one working environment, where the geometry is parametrically designed, and subsequently analysed in the virtual wind tunnel through the Swift extension for Grasshopper. The Computational Fluid Dynamics analysis results retroactively help decide which of the design options performs the best in the given wind conditions.

1. Introduction

The paper presents a methodology for the wind-driven designing, with the wind factor incorporated into the early stage of architectural form-finding. The recent decades showed that aiming only on the quality of the interior environment when designing buildings will not suffice in the future changing climate [1, 2, 3]. Climate-conscious design as a form of adaptation to climate changes along with substantial and sustained reductions in greenhouse gas emissions can limit the consequences of ongoing climate change [4]. Moreover, to create a comfortable outdoor environment for pedestrians, the factors such as the wind effects, or outdoor thermal comfort should be fully considered throughout the whole process of designing the built environment [5].

1.1. Built environment shaping the wind flow

The rapid pace of improving hardware and software, including CFD (Computational Fluid Dynamics), as well as parametric design techniques, motivates the research of reciprocal interactions of architecture and the wind [6], enables exploring the aerodynamic behaviour of building shapes [7, 8], natural ventilation of urban districts and buildings [9], prediction of pollutant dispersion from high-density urban areas [10], or utilizing the wind for renewable energy not only in high-rise buildings [11] but also in low-rise residential areas [12]. Architectural design, from urban configurations, through building shapes, to the local form of the façade, impacts the character of the wind flow, as well as the creation of turbulence, and acceleration or deceleration of the wind speed, which further influences the wind pressure on buildings.

1.2. Designing the shape-morphing facades

The progressive computational design enables the creation, as well as single or multi-criteria optimization of urban and architectural designs, as early as in the conceptual design stage. More specifically, techniques such as parametric designing contribute to creating an environment-conscious, performance-
oriented architecture, morphing its shape while interacting with the fluctuating external or internal conditions such as solar radiation, changing temperatures and temperature extremes, precipitation, the motion of the building occupants or the dynamic wind force [13, 14].

2. Design method
The methodology for designing architecture in the era of changing climate is introduced in a case study in Stockholm. The former industrial docks are typical for the turbulent wind conditions, created by the densely built cylindrical concrete silos, which are up to 35 meters high and up to 30 meters wide. The wind-driven design method consists of the following steps: i) firstly, the wind situation of the case study site is examined without architectural intervention, ii) secondly, the influence of an aerodynamic shape, designed between the concrete silos, is investigated, iii) and thirdly, the influence of the wind-adaptive building skin on the wind flow, as well as the wind pressure acting on building surfaces, is investigated.

2.1. CFD simulations of the case study site
The first step in the climate-conscious, wind-driven design is the analysis of wind conditions (figures 1 and 2). The CFD simulations predict where the turbulence (T), as well as acceleration (A), will occur. The wind pressure on silos (positive + and negative -) is depicted in the perspective view in figure 2. Swift for Grasshopper is used for the CFD analysis. The visual algorithmic tool Grasshopper is a plugin for the 3D modeling software Rhinoceros. Swift for Grasshopper runs on the well-known open-source CFD software OpenFOAM®, with the working environment programmed for the parametric use in Grasshopper. The calculations are performed using the RANS (Raynolds-Averaged Navier Stokes) turbulence model. It is set that the simulations should either run for 500 iterations, or converge when the calculated initial residuals of pressure $p < 4 \times 10^{-2}$, along with all velocity components $v_{x,y,z} < 1 \times 10^{-2}$, and $kε < 1 \times 10^{-2}$. The convergence criteria are relatively mild as the solution is sought for a large-scale, urban area. The tests are performed with extreme wind speed, 24 m/s, which is used in Stockholm for the structural design of buildings [15]. The surface roughness is set as ‘skimming – densely built up, 1H separated large obstacles, buildings’, implying that the roughness factor $c_r(z)$ is equal to 1. In the FVM (Finite Volume Method) analysis, the size of one calculation volume in the wind tunnel is 3×3×3 meters, whereas the size of one calculation volume in the refinement region around the tested geometry is 2×2×2 meters. The calculations stopped after reaching 500 iterations, which took more than 36 hours.

Figure 1. CFD analysis of a part of the former industrial site with silos and few other buildings on the western side (top view at 1.8 m from the ground).
Figure 2. CFD analysis of a part of the former industrial site (perspective view). T – turbulence, A – acceleration of the wind flow.

2.2. Design interventions
Design interventions in the former industrial park include a protecting membrane around swimming pools in Zone 1, silos wrapped in the electricity-producing membranes in Zone 2, and an auditorium with a membrane building skin in Zone 3. Three shapes winding around the silos, which are designed parametrically in Grasshopper, deflect the wind in Zone 1, accelerate the wind in Zone 2 [16], and act as a minimum resistance to the wind flow in Zone 3 (figure 3). This paper will focus on one of the shapes, the auditorium in Zone 3. The parametric design of architectural shapes enables the fast creation of several design options.

Figure 3. Architectural interventions around concrete cylindrical silos affecting the wind flow.

2.3. Wind-adaptive building skin
Tensegrity-membrane building skin, adapting to the wind in real-time, was designed and tested as a prototype in the previous research [17]. Thanks to the tensegrity geometry, as well as the material properties of the structure, every element of the adaptive façade bends in the acting wind (figure 4). Depending on the intensity and the direction of the wind flow, adaptive elements passively (with the embedded material and geometrical properties) respond to the dynamically changing wind conditions. Although lightweight, such building skin can withstand high wind speeds by distributing the wind loads within the adaptive structure. One of the benefits of the passive (without computer control) response is
the reversible shape adaptation under load. The developed adaptive skin is applied to the designed auditorium shape in Zone 3. For the investigation of the performance in the wind, the wind-induced shape response of the tensegrity-membrane skin is simplified, neglecting the tensegrity sub-structure. For the CFD evaluation in the early design stage, however, such simplification is possible as the goal is to quickly compare the wind performance of different shape options in the wind. The material characteristics of the membrane, used as a building skin, are derived from [18] and described in table 1. In the Kangaroo 2 [19] simulations, the skin of the proposed aerodynamic shape consists of the membrane and is loaded by the wind force. The wind speed 24 m/s is represented by pressure $p_w = 360$ Pa, derived from the Bernoulli’s equation:

$$p_w = \frac{1}{2}(\rho v^2)$$

(1)

where $\rho$ is the density of air (the value recommended by the EN standard [15] for calculations related to the wind loads is $1.25$ kg/m$^3$) and $v$ is the wind velocity in m/s.

### Table 1. Material properties of the membrane in the wind-adaptive element.

| Material and thickness | Stiffness $k$ (N/m) | Young’s Modulus $E$ (Pa) | Pre-tension $0=\text{max.}; 1=\text{min. (-)}$ |
|------------------------|---------------------|--------------------------|-----------------------------|
| tensile fabric         | 84                  | $150$                    | $16.5\times10^7$            |
| h (mm)                 |                     |                          |                             |

**Figure 4.** A scheme of the adaptive skin application with a zoom on one adaptive element.

2.4. **CFD analysis of the designed shape in Zone 3**

The wind analysis of the proposed aerodynamic shape, with and without the intended adaptive skin, is performed in Swift for Grasshopper (figure 5). The same boundary conditions as in the original site analysis, as well as the same initial wind speed 24 m/s is used in the Zone 3 simulations. The wind tunnel (the CFD domain), however, is smaller; the computational volumes are smaller, meaning the wind tunnel will consist of more computational volumes to capture the flow in greater detail. The cell size of the wind tunnel is $3\times3\times3$ meters, whereas the cell size in the refinement region around the investigated geometry is $1\times1\times1$ meter. The convergence criteria are the same as in the site analysis. The calculations are set to run until reaching convergence. By the given boundary conditions, the simulations converged for smooth shape variant and dimpled shape variant with adaptive building skin in 650 iterations and 352 iterations, respectively.

3. **Results and conclusion**

The designed aerodynamic shape, winding around silos in Zone 3, influences the wind character in its vicinity. The aerodynamic shape directs the wind flow around the silos and contributes to the reduction of the positive and negative surface wind pressure on the three closest silos. The results of the three CFD simulations focus on surface pressure and suction reduction achieved by the designed architecture. The pressure used in Swift is kinematic pressure with units in m$^2$/s$^2$. The analysed case without any architectural intervention shows the surface pressure on the silos 1, 2, and 3 in Zone 3, ranging from 1091.64 to $+315.50$ m$^2$/s$^2$ (-1364.55 to $+394.38$ Pa) (figure 2). Now, with the designed aerodynamic
shape, the surface pressure on the three silos ranges from $-1048.26$ to $+411.89$ m$^2$/s$^2$ ($-1310.33$ to $+514.86$ Pa). If the adaptive skin is applied to the aerodynamic shape creating a rough, dimpled surface, there is an even greater reduction of the wind suction; the pressure ranges from $-864.96$ to $+410.50$ m$^2$/s$^2$ ($-1081.20$ to $+513.13$ Pa) (figure 5). The results show that the utilization of computational tools in the early design phase of architectural designing enables a fast exploration of different design proposals. The paper demonstrates that wind-driven architectural design can positively change the wind microclimate around buildings by deflecting the wind from the pedestrian level (1.8 m above the ground). Moreover, architectural interventions can contribute to reducing the negative effects of the wind, such as wind pressure and wind suction, leading towards lighter structures in architecture. To conclude, the application of the wind-adaptive building skin instead of regular, smooth surfaces could contribute to i) much lighter building skin structures even for the more extreme winds, ii) reduction of wind pressure on surfaces, especially the reduction of wind suction, and iii) creating an entirely new reading of the wind through real-time architectural response.

Figure 5. The aerodynamic shape with the smooth building skin (top) and the variant with the wind adaptive building skin (bottom) (top view at 1.8 from the ground).

4. References

[1] Snow M and Prasad D 2011 Climate Change Adaptation for Building Designers: An Introduction, Environment Design Guide pp. 1–11

[2] Pellitteri G, Lattuca R, Concialdi S, Conti G and De Amicis R 2009 Architectural shape generating through environmental forces Joining Languages, Cultures and Visions: Proc. 13th Int. CAAD Futures Conf. (Montréal) pp 875–886

[3] Kuismanen K 2008 Climate-conscious architecture: Design and wind testing method for climates in change University of Oulu

[4] Pachauri, R K, Meyer L A 2014 Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC Geneva Switzerland
[5] Jin H, Liu Z, Jin Y, Kang J and Liu J 2017 The Effects of Residential Area Building Layout on Outdoor Wind Environment at the Pedestrian Level in Severe Cold Regions of China Sustain. vol 9 no 12 pp 1-18

[6] Kormaniková L, Achten H, Kopřiva M and Kmeť S 2018 Parametric wind design Front. Archit. Res. vol 7 no 3 pp 383–394

[7] Mooneghi M A and Kargarmoakhar R 2016 Aerodynamic Mitigation and Shape Optimization of Buildings: Review J. Build. Eng. vol 6 pp 225–235

[8] Kabošová L, Kmeť S and Katunský D 2019 Digitally Designed Airport Terminal Using Wind Performance Analysis Buildings vol 9 no 3 pp 102–116

[9] Kim H J and Kim J S 2018 Design methodology for street-oriented block housing considering daylight and natural ventilation Sustain. vol 10 no 9 pp 1-22

[10] Yuan C et al. 2019 Multilayer urban canopy modelling and mapping for traffic pollutant dispersion at high density urban areas Sci. Total Environ. vol 647 pp 255–267

[11] Ishugah T F, Li Y, Wang R Z and Kiplagat J 2014 Advances in wind energy resource exploitation in urban environment: a review Renew. Sust. Energy Rev. vol 37, pp 613–626

[12] Zhou H, Lu Y, Liu X, Chang R and Wang B 2017 Harvesting wind energy in low-rise residential buildings: Design and optimization of building forms J. Clean. Prod. vol 167 pp 306–316

[13] Turrin M, Buelow P Von, Kilian A and Stouffs R 2014 Parametric modeling and optimization for adaptive architecture Intelligent Computing in Engineering EG-ICE International Workshop 1–8

[14] Biloria N and Sumini V 2009 Performative Building Skin Systems: A Morphogenomic Approach towards Developing Real-Time Adaptive Building Skin Systems Int. J. Archit. Comput. vol 7 no 4 pp 643–675

[15] Eurocode 1 2010 Actions on structures, Part 1-4: General actions. Wind actions, EN 1991-14:2005 Brussels

[16] Kormanikova L, Chronis A, Kmet S and Katunsky D 2018 Wind-formed Architectural Shapes Proc. 36th eCAADe Conf. vol 2 pp 377–384

[17] Kabošová L, Foged I W, Kmeť S and Katunský D 2019 Hybrid design method for wind-adaptive architecture Int. J. Archit. Comput. vol 17 no 4 pp 1–16

[18] Yang S and Sultan C 2016 Modeling of tensegrity-membrane systems Int. J. Solids Struct. vol 82 pp 125–143

[19] Preisinger C 2013 Linking Structure and Parametric Geometry Archit. Des. vol 83 no 2 pp 110–113

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