The search for an optimal architectural shape using wind performance analysis

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Abstract. The rapid enhancement of computers’ power and the boom of open-source software development have offered a broad range of possible applications in architectural design. Grasshopper is a visual programming language developed for the 3D CAD modeling program, Rhinoceros. Utilizing Grasshopper’s free software extensions, it is possible, among other things to evaluate the environmental performance of architecture in the early conceptual stage. This paper introduces a novel approach to architectural designing presented in a case study in the extreme environment of Reykjavík’s airport. The shape of the airport building formed within this case study can be parametrically changed, and the performance of the various shape modifications in the wind can be tested. Using Ladybug and Swift for Grasshopper, the wind situation at the airport is analyzed, and the aerodynamic shape of the proposed airport building is evaluated in the prevailing easterly winds. The proposed bio-climatic architectural design approach incorporates the surrounding micro-climatic conditions, wind in particular, as a driving factor already in the phase of first design ideas. The parametrically developed airport is formed with regard to the pedestrian wind comfort, as well as airport traffic safety.

1. Introduction

Due to the rapid development of digital design tools, it becomes possible for architects and designers to relatively seamlessly incorporate simulations such as environmental [1, 2] or structural analysis [3, 4] to their projects in the early conceptual phase of architectural design. Moreover, some of the recently developed analysis software is accessible free of cost which unfolds new perspectives in design. Computer simulations utilized in the early conceptual stage, predicting the behavior of environmental phenomena such as solar or wind fluxes can reveal a lot about the performance of the future building, a building cluster, or a building’s structural system. The results of such analyses can be employed to adapt the design, the building envelope or its structure. Such a design loop can be applied until an optimal solution is achieved creating a basis for nature-adapted designs. When applying such a design approach in the early stages of design, the goal is to do it in the most time and cost-effective way and simultaneously not to lose on precision.

1.1. Wind-driven design

The air movement is usually perceived as a negative phenomenon in the building design, although sometimes the effects of wind can be beneficial. On the one hand, the air movement in interiors is necessary for natural ventilation, on the other hand, the speed of moving air has to stay within limits for a comfortable indoor climate. The wind speed and the flow pattern are shaped by the relative position and form of the buildings [5] in the outer environment which can result in an acceleration of the flow or unpleasant turbulence. By the lower ambient temperature, the pedestrians perceive the wind flow more negatively. From the structural point of view, the wind acceleration and turbulent flow intensify the
loads on structures. It might be fair to assume that the wind-driven design could not only contribute to regulating the wind flow, as well as wind pressure on buildings and around them, but also positively affect the comfort of their inhabitants.

Design strategies incorporating wind flow suggest that an improved, optimal natural ventilation of interiors can be achieved [6], or buildings can be adequately placed and rotated to benefit from the cooling effects of the wind [7], or the negative effects of the wind can be attenuated using small architectural interventions [8]. The following case study demonstrates an architectural design strategy that incorporates the specific wind conditions of Reykjavik’s airport and regulates the wind flow pattern using the parametrically created airport terminal building. Three design variants of the streamline-shaped airport terminal are evaluated based on their aerodynamic properties.

2. The case study in Reykjavik
Designing with the wind in the very early design phase urges to utilizing a digital approach, including Computational Fluid Dynamics (CFD) simulation tools. Such digital approach is necessary for a relatively fast evaluation of the various design options. In the early conceptual stage, the time of the wind simulation, the cost of the software and the precision of the results are the key factors. The most suitable combination for the analysis in the conceptual stage is a fast, but precise enough analysis (Figure 1). In the later design phases, a professional CFD analysis or wind tunnel experiments can be applied.

The design approach introduced in this paper consists of the following steps: (1) the wind situation of the case study site is analyzed based on the data obtained from the EnergyPlus web database, (2) the 3D shape of the airport terminal is developed parametrically using Grasshopper for Rhinoceros (Rino), (3) various shape modifications can be created thanks to the parametric approach, (4) a new open-source wind analysis tool for Grasshopper called Swift is used for evaluating three shape alternatives in the prevailing easterly wind flow, (5) Paraview is employed for post-processing the obtained results outside the working environment of Grasshopper and Rhino, (6) in the last step, the performance of the designed shapes in the wind is evaluated. Looping the design steps directs the process into finding an optimal shape option (Figure 2).

![Figure 1. The relation of the time, and the precision and cost requirements for various wind analysis techniques.](image1)

![Figure 2. The steps in the proposed design approach. The arrows indicate the loop for achieving the optimal final shape.](image2)
2.1. Prevailing winds in Reykjavík
EnergyPlus digital data source [9] is used to obtain representative wind data for Reykjavik’s airport in the *epw format. A plug-in for Grasshopper called Ladybug requires such *epw file to generate a graphical wind rose (Figure 3). The wind rose suggests that the easterly winds are dominant in the given locality for, on average, 15.64 % of hours per year. The easterly wind’s average wind speed is 6.2 m/s. This value is used in the CFD simulations. The average wind gust speed for all wind directions reaches 25 m/s. Moreover, the wind temperature is usually not exceeding 10°C. This combination of ambient conditions is very unpleasant for pedestrians and workers at the airport.

![Figure 3. The wind rose of Reykjavík’s airport.](image)

2.2. Parametrically-created airport terminal building
The benefits of parametric designing lie in the possibility to experiment with the selected variables and obtain a new final shape for every change in parameters. In this case study, two parametric variables influence the final shape: a planar closed curve and an arbitrary number of attractor points. The representation of the final shape is a result of the form-generation process decided by the designer. In this paper, the curve is drawn by the designer and represents the footprint of the future airport terminal building. Subsequently, three attractor points are determined in the same plane. The proximity of attractor points to the planar curve influences the final form and forces it to close towards the wind (Figure 4).

![Figure 4. The variables that influence the final form in the parametric definition (left), the final shape (right).](image)
2.3. CFD simulations in Swift for Grasshopper

The goal of the research is to simplify the wind analysis process in the early design stages. Architects tend to use Grasshopper for a wide range of environmentally-related design tasks where multiple design aspects are considered. In the field of parametric CFD analysis, Swift for Grasshopper is a recent extension that works on the platform of the powerful CFD tool OpenFOAM which guarantees the reliability of the results. ‘SimpleFoam’ (semi-implicit method for pressure-linked equations) algorithm executes the calculations of the Navier-Stokes equations. RAS (Reynolds-averaged stress) turbulence model is used for steady-state simulations [10]. Three designed shape variants are analyzed using Swift. The following input conditions are defined: (1) the wind speed is set to 6.2 m/s, (2) the simulations run in 250 iterations to meet the convergence criteria, i.e., the convergence tolerance of $10^{-5}$ for the velocity components $U_x$, $U_y$, and $U_z$. The results of the simulations are subsequently post-processed in Paraview external visualization software. For a better visual comparison, the data range of velocity and pressure is customized for all three design options. The range of values for the wind velocity is set from the minimum value 0 m/s, represented in blue color, to a maximum value 10 m/s, displayed in red color. The range of pressure values is set from -40 to 20 m$^2$/s$^2$, again on the color scale from blue to red (Figure 5).

![Figure 5. Three examined shapes: bottom row – surface pressure [m$^2$/s$^2$], upper row – velocity [m/s].](image)

3. Conclusions

The proposed bio-climatic architectural design approach combines 3D modeling software Rhino with open-source extensions for a smooth integration of wind analysis into the conceptual design stage. It offers a fast and precise enough way for architects and designers to evaluate the performance of their designs in the specific wind conditions. By incorporating parametric designing, such technique leads to finding an optimal building shape based on its desired interaction with the wind flow. The design approach is presented in a case study in Reykjavik, Iceland. The proposed parametric definition in Grasshopper enables to create shape modifications of the designed airport terminal building. Three shapes are tested in the easterly winds, prevailing in the area. The wind flow around the proposed shapes, as well as wind pressure on the buildings’ envelope, is observed. All variants are aerodynamic; the shape 1 causes mild turbulence on the leeward side. Shape 2 alters the wind flow causing turbulence on the leeward side, above the building, and in the intended wind-protected zones. Shape 3 performs as the most streamlined and aerodynamic in the observed wind situation. The surface pressure as a result of the wind loads is examined too. The results prove the aerodynamic properties of the three shapes. The wind flow altered by shape 2 causes the highest negative surface pressure, i.e., suction when compared to the other two options, whereas the positive surface pressure is the highest in the case of shape 1. It might be debated, how precise is the interpretation of the results based on pure observation. However,
the proposed design loop is developed for the very early stages of design with an intention to direct the wind-influenced design to the next design stages. The search for an optimal shape guarantees that the wind fluxes will not be interfered by the designed building shape and the pedestrian wind comfort around the building in the wind-protected zones, as well as airport traffic safety, will not be affected.

4. References

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