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APPLICATION OF CFD ANALYTICAL TOOLS IN ARCHITECTURAL DESIGN IN THE CONTEXT OF WIND LOADS – PART 2

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Abstract
The second part of the article discusses the assessment of extreme weather conditions on architecture in the era of climate change with the aid of CFD analysis tools. Computer simulations such as CFD have opened up new possibilities for design and research by introducing environments we can manipulate and observe. The article presents two case studies of high-rise buildings: Plac Unii (2013) and Q22 (2017) located in Warsaw, showcasing the increasing role of new technologies, particularly CFD simulation tools, in studying the aerodynamics of urban environments. The paper includes CFD wind studies of the buildings and their urban surroundings performed in Autodesk Flow Design.

Keywords: architecture; wind analysis; CFD; wind tunnel; research based design

INTRODUCTION

The idea of streamlines is an important concept in the study of aerodynamics. A streamline is a path traced out by a massless particle as it moves with the flow. For most buildings, aerodynamic damping has positive effects. This is beneficial in reducing the resonant dynamic response of the building. Wind flow over buildings leads to separation and hence a complex spatial and temporal mechanism that governs the nature and intensity of aerodynamic forces. This complexity mainly comes from the transient nature of incident turbulent winds and the fluctuating flow pattern in the separation bubble. The study of building aerodynamics is vital for the evaluation of cladding pressures, drag, shear, and uplift forces that are essential for safe and economic design. Flow separation makes it challenging to estimate loads without referring to direct physical and/or computational simulation. For several decades, aerodynamic testing has been employed for the estimation of wind pressures and forces on buildings.

Wind is the horizontal or almost horizontal movement of air relative to the Earth's surface caused by a pressure difference. In open, undeveloped areas, its operation is modified by the topography and material diversity of the substrate, which heats up differently. In highly urbanized areas, aerodynamic phenomena at the level of building heights are very complex. The air does not fall on a flat surface, but on a strongly deformed surface, most of which is hardened, and therefore heats up much more intensely than the surrounding area [K. Zielonko-Jung 2018]. Additional loads appear due to aerodynamic interference and various constrictions that accelerate the flow. In many cases, mainly high-rise buildings, the impact of wind often determines the shape of the structure itself, for example it forces the use of rounded corners or additional elements in the façade placed in the corners of the buildings, making structural openings or installing vibration dampers [T. Lipecki 2015].

In contemporary architectural design it is necessary to accurately and precisely assume the wind load. Detailed study of local geographical and environmental conditions can be the basis for long-term strategies in the architectural design process. The impact of extreme wind is in many cases a factor determining architectural and structural design. Various forms of wind impact and the loads they cause may constitute values that influent dimension the cross-sections of structural elements.

1. CLIMATE CHANGE RESPONSIVE ARCHITECTURE

Climate change is a recent topic that needs to be addressed much more in architectural design education to prepare students for unforeseen challenges. Buildings are designed for a specific climate yet they often have a lifetime of 50–100 years and climate change may require a building to operate over a range of climatic conditions as a result of the impact of global warming. Winds are commonly classified by their spatial scale, their speed and direction, the forces that cause them, the regions in which they occur, and their effect. Undoubtedly, weather phenomena in the era of climate change in many areas of the Earth will be characterized by extreme winds (hurricanes, typhoons, etc.) and where there are tall or long-spanning structures, flow loads are the most important at the design stage.

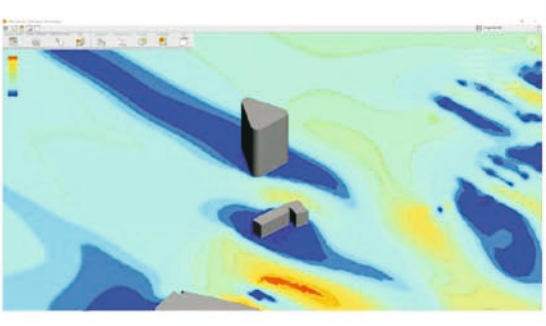
Climate Change is impacting global wind patterns in many ways. In the era of climate change, there is an urgent need for climate responsive architecture adapting to changing environmental conditions. This means resistance to extreme weather that includes heat waves, cold waves and heavy precipitation or storm events, such as hurricanes and cyclones. Weather anomalies that are forecast in this dynamic process will mark the development of new ways of building, especially with regard to architectural design. Air circulation within and around buildings and its surroundings can be examined in both physical and virtual ways. Airflow can impact all aspects of a building design. Wind and airflow affect urban and building design strategies such as natural ventilation. Airflow has a direct impact on the comfort levels of using a building, and the following factors should be considered:

- Air circulation can impact passive cooling and overall energy efficiency of the building;
- External airflow can impact internal ventilation;
- Wind airflow loads on the main structural elements (overall wind loads);
- Wind airflow loads on the facade, openings or roof details and ancillary building items;
- Localized wind anomalies effects on air quality, particulates and pollution around buildings on external or public spaces in the built environment.

2. CFD IN ARCHITECTURAL DESIGN

Using CFD analysis, it is possible to find the suitable information (local wind velocity, convective coefficients, and solar radiation intensity) for optimal orientation, site and location selection of buildings. It is becoming increasingly important to provide occupants comfort in pleasant building environments. Architects and wind engineers are often asked to look over the design (orientation, site, location and gaps between the surrounding buildings) in the formative planning stage of construction. Computational fluid dynamics modeling, or CFD, is based on the principles of fluid mechanics, utilizing numerical methods and algorithms to solve problems that involve fluid flows. The equations governing fluid motion are the three fundamental principles of mass, momentum, and energy conservation. CFD has many applications in the field of architectural design. It can be used to optimize the design of both internal and external spaces of a building by predicting how it will behave under specific conditions.

Tab. 1. Application of CFD in architectural design

CFD ANALYSIS	ARCHITECTURAL DESIGN
	– optimal orientation, site and location selection of buildings – ventilation study in buildings – heat balance calculation – thermal analysis – renewable energy generation – wind assessment for urban planning and architecture

Source: prepared by the author

The role of the parametric model in modeling construction information in BIM technology was described by K. Januszkiewicz and K.G. Kowalski [2020]. The process of parametric modeling of an object's surface can be linked directly to CFD analyses included in the Digital Project GT software. The results of these analyses allow the optimization of the shape of the form due to wind loads [K. Januszkiewicz 2012].

In the selection of building site and location, among other local geographical and environmental conditions, wind loading plays an important role. For example, in the case in which two buildings at a location exist side by side with a gap, when a volume of wind blows around the ends of the buildings and through the gap, the sum of flow around each building and then its velocity increases as it travels through the gap, at the expense of pressure loss. As a result, there is a build up of pressure entering the gap, which leads to higher wind loads on the sides of buildings. When wind blows over the face of a high rise building, a vortex is created by the downward flow on the front face. The wind speed in the reverse direction near the ground level may have 140% of the reference wind speed, which can cause severe damage (especially to the roof of building). Such damage to buildings can be prevented if the effects of wind loading are considered in the early stage of construction of a building [K. Klemm 2022].

Recently ventilation and its related fields has become a great part of wind engineering. The ventilation study in buildings is done to find the thermally comfortable environment with acceptable indoor air quality by regulating indoor air parameters (air temperature, relative humidity, air speed, and chemical concentrations in the air). CFD finds an important role in regulating the indoor air parameters to predict the ventilation performance in buildings. The ventilation performance prediction provides the information regarding indoor air parameters in a room or a building even before the construction of buildings. These air parameters are crucial for designing a comfortable indoor environment, as well as good integration of the building in the outdoor environment. This is because the design of appropriate ventilation systems and the development of control strategies need detailed information regarding the parameters of airflow, pollutant and contaminant dispersion and temperature distribution. A ventilation study can be done using wind tunnel investigation (experimentally) or by CFD modeling (theoretically). Natural ventilation systems may be preferred over forced ventilation systems in some applications, as it eliminates or reduces the need for a mechanical ventilation system, which may provide both fan energy and first-cost savings. In the present era, due to development of a lot of CFD software and other building performance simulation software, it has become easier to assess the viability of natural/forced ventilation systems in a building. In order to reduce heat losses from buildings, CFD thermal analysis can be done for the optimum configuration of composite walls, roof and floor. In buildings, heat transfer takes place in all modes i.e. conduction, convection and radiation through walls, roof and floor of buildings.

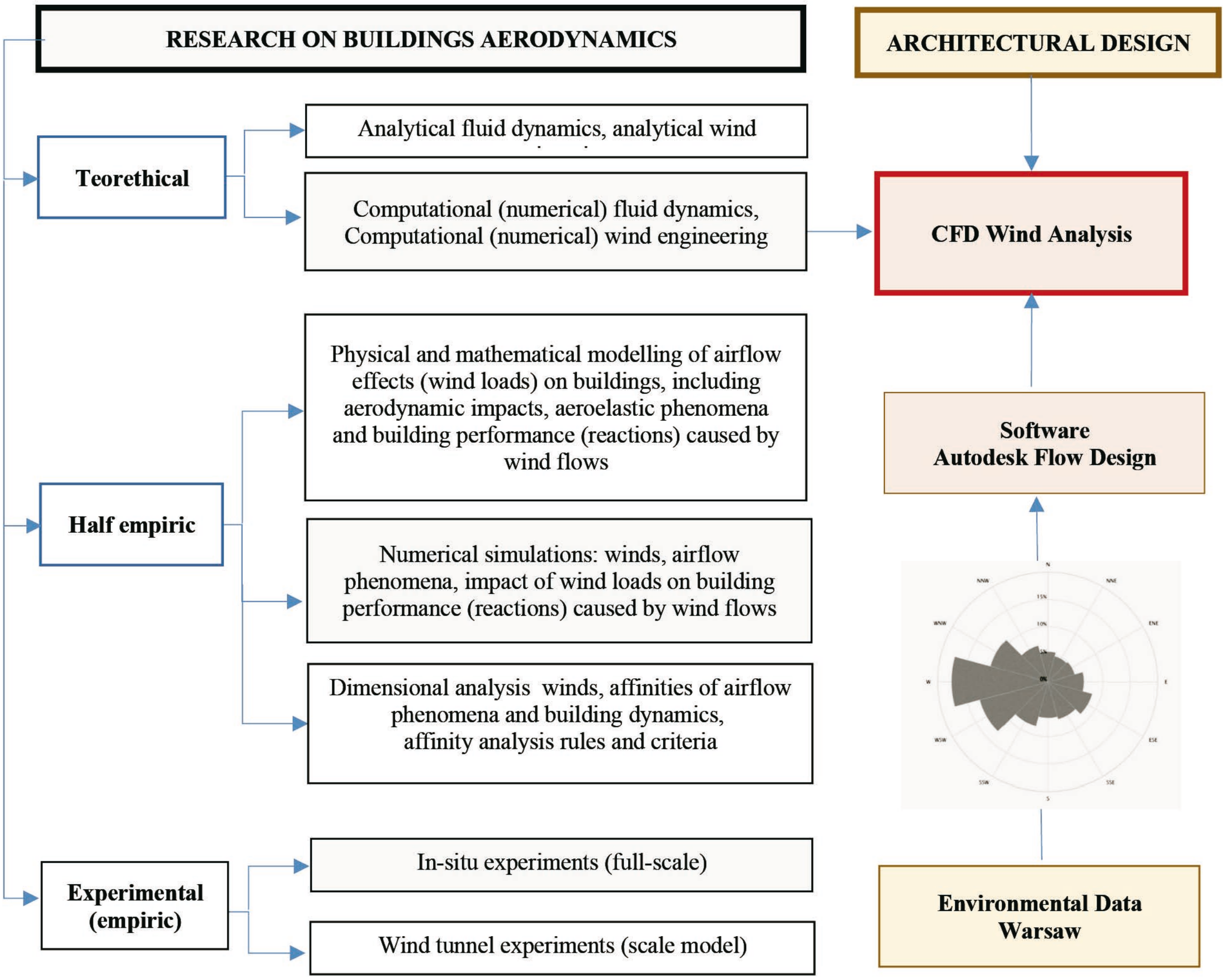
CFD simulation may be used to assess windflow over small wind turbines and solar panels, which help to define overall efficiency of the building. The impact of renewable energy sources on the architecture of selected buildings in Poland after 2004 was described by J. Juchimiuk. [J. Juchimiuk 2018].

3. WIND ANALYSIS OF Q22 AND PLAC UNII HIGH-RISE BUILDINGS IN WARSAW

Tall buildings are particularly prone to wind loads and aerodynamic phenomena. One way to minimize wind-induced vibrations in tall buildings is to focus more on their shapes in the design stage. High-rise buildings in cities adversely affect wind regimes by changing the air currents in their surrounding areas. In particular, extreme climate phenomena caused by climate change are stronger and more frequent, causing damage in cities. To better understand wind behaviors around high-rise buildings, actual measurements are necessary to determine the environmental assessment of the wind effect. Two high-rise buildings: Q22 (2017) and Plac Unii (2013) located in Warsaw were analyzed by the author.

Wind engineering by A. Flaga is the first monograph in Poland on wind engineering. It presents issues related to, among others, the impact of wind on the natural environment and people, as well as on buildings and engineering structures. The use of wind as an energy source was discussed, and the topic of natural disasters caused by extreme winds was raised. Particular attention was paid to current research on building aerodynamics (Tab. 2) and the issues of safety and reliability of structures exposed to wind loads [A. Flaga 2005].

Tab. 2. Research on building aerodynamics, CFD Wind Analysis using Autodesk Flow Design.



Source: prepared by the author based on A. Flaga 2008

3.1. Methodology

Air flow is highly determined by the layout of surrounding buildings. The CFD analysis of case study buildings was carried out by the author using Autodesk Flow Design software according to the following methodology:

1. Flow problem formulation.
2. Geometry modelling.
3. Establishing the Boundary and initial parameteres of analysis.
4. Voxel grid generation.
5. Establishing Simulation strategy and wind speed parameters.
6. Simulation.
7. Monitoring.

The Autodesk Flow Design analysis mechanism is presented in the article at the TOI-Pedia (digital repository of the University of Delft): "*The Fluid Dynamics simulation uses a special type of geometry to make the fluid calculations possible, called voxels (volume pixels). These are 3 dimensional pixels, basically a set of cubes nicely stacked into a container. Every cube will contain the mathematically defined properties of a fluid and therefore behave like a particle of fluid. A cube (voxel) will behave like one mathematically defined object, calculating the forces, pressure and temperature placed on the cube and then emitting the result to its neighboring cubes. Transmitting effects of heat, pressure and movement throughout the container holding all the cubes*" (Fig. 1a–b) [TOI: Design Informatics, 2020].

The aim of the wind study of two high-rise buildings performed by the author was to determine the impact of the architectural form of the high-rise buildings on their surroundings. The heights of buildings and the widths of individual street canyons and the heights of the buildings in 3D models used in wind analysis were determined by on-site visits and by analyzing Cadmapper, Geoportal 2 and Google Earth 3D models. Due to the lack of access to accurate data, accuracy of up to 5m was assumed.

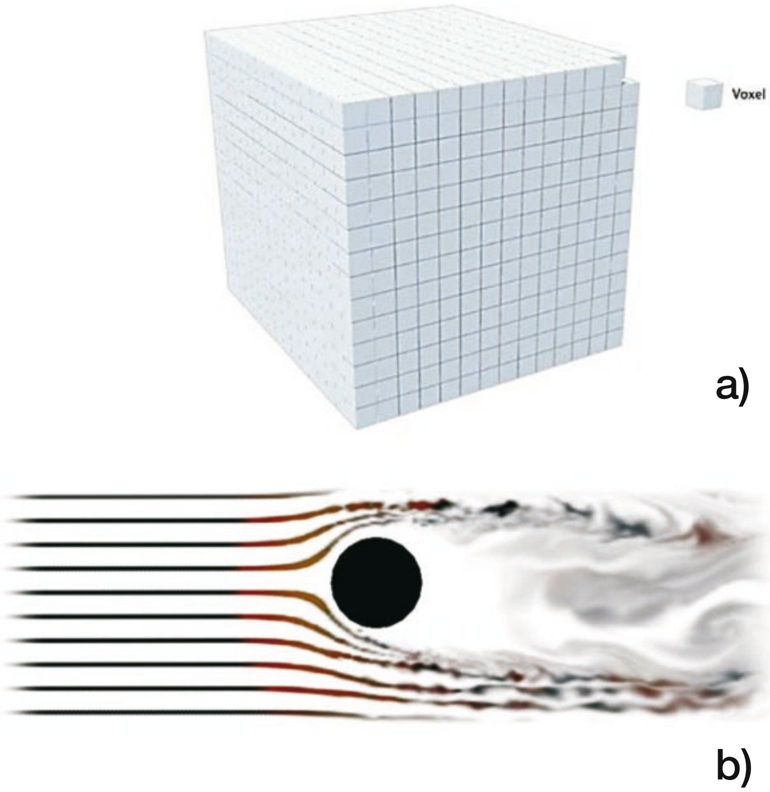


Fig. 1a–b. The Fluid Dynamic simulation; source: TOI: Design Informatics 2020

A similar study of urban areas of central Warsaw was performed using ANSYS Fluent software by A. Chudzińska, M. Poćwierz and M. Pisula in 2021. Analysis of aerodynamic phenomena in a selected quarter of building developments in downtown Warsaw with reference to air pollution covered about 43 ha and included densely developed tenement houses, high-rise buildings and more extensive volumes, such as the Złote Tarasy Shopping Center (ZT) and the Palace of Culture and Science. [A. Chudzińska, M. Poćwierz, M. Pisula 2021].

3.2. Case study: plac unii high-rise building, Warsaw (2013)

Plac Unii – an office and commercial complex at ul. Puławska 2 near The Union of Lublin Square, designed by APA Kuryłowicz & Associates Studio, was realized in Warsaw in 2010-2013. The skyscraper was properly used as a spatial dominant located at the end of ul. Puławska. However, there are reasonable concerns about the unfavorable impact on the viewing openings in the area of Łazienki Park, and in particular the disruption of the view of the Belweder Palace by the silhouette of the skyscraper [H. Markowski, K. Owczarczyk, K. Szulborski 2014].

Fig. 2a–d. Plac Unii building, Warsaw, APA Kuryłowicz; source: photo by the author (2023).

Fig. 2e–g. Plac Unii building, Warsaw, APA Kuryłowicz; source: photo by the author (2023).

The Plac Unii complex consists of three buildings, the tallest of which is a 90-meter tower with a form inspired by the New York Flatiron building constructed in New York in 1902 (Fig. 2a–g). The form of the building is compact. Rounded corners of the tower reduce the impact of wind on the structure of the object. The use of an extended skyscraper base in the form of two lower buildings connected by glass roofs also reduces the impact of the wind. This type of solution for shaping the body of a tall building significantly improves the windy climate in its surroundings.

Model tests and study analyses of the impact of wind on a tall building were carried out by the team of prof. A. Flaga at the Wind Engineering Laboratory of the Cracow University of Technology in 2008 [A. Flaga 2015]. Dynamic pressure measurements on the walls of a building model used wind flowing from 33 different directions. Determination of basic patterns of equivalent wind impact on this building for static and strength calculations are shown above (Fig. 3a–b.).

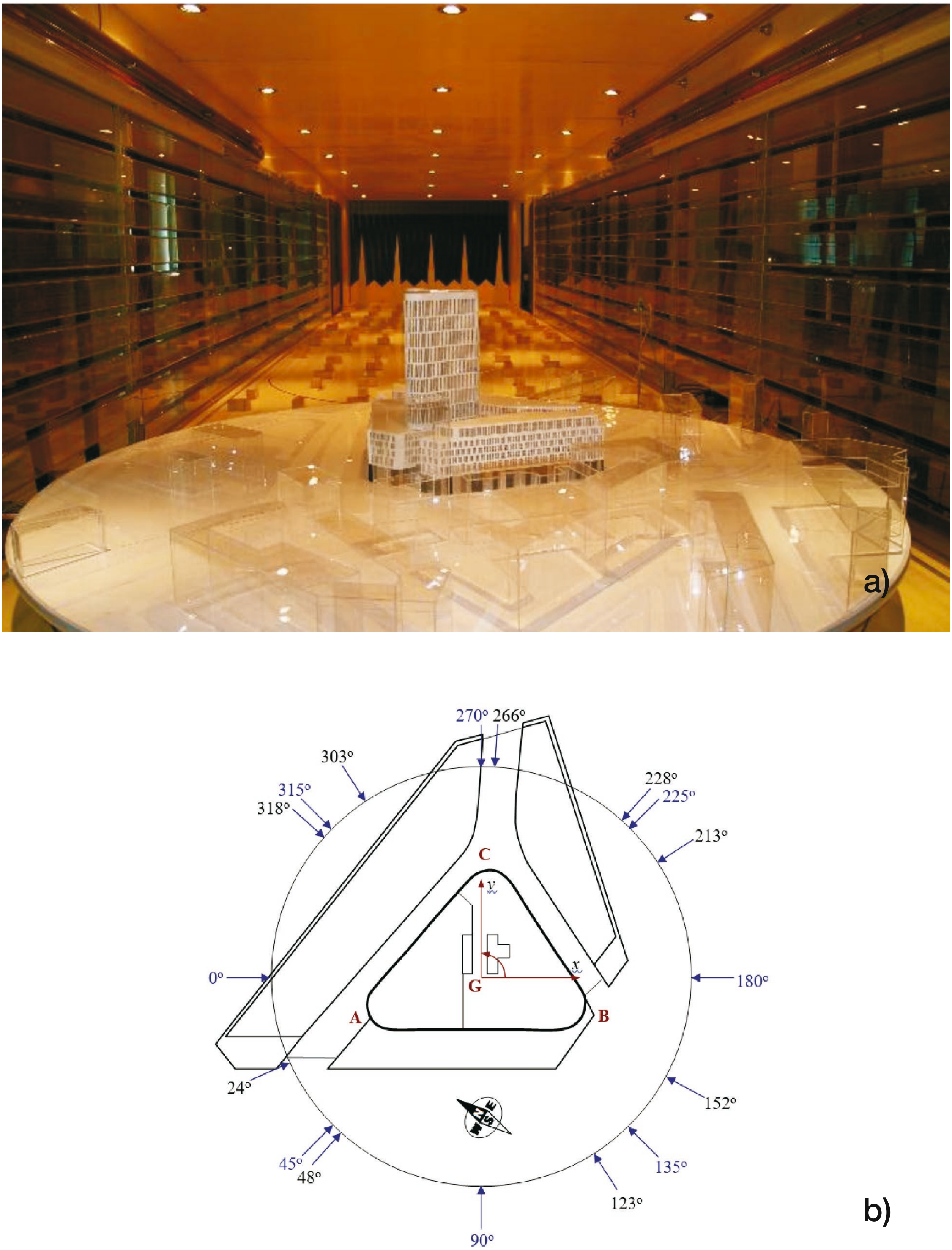


Fig. 3a–b. Wind analysis Plac Unii high-rise building, a) view of the model in the measurement space of the wind tunnel, b) analyzed directions of wind inflow during research;; source: A. Flaga 2015, Laboratory of Wind Engineering, Cracow Univ. of Tech.

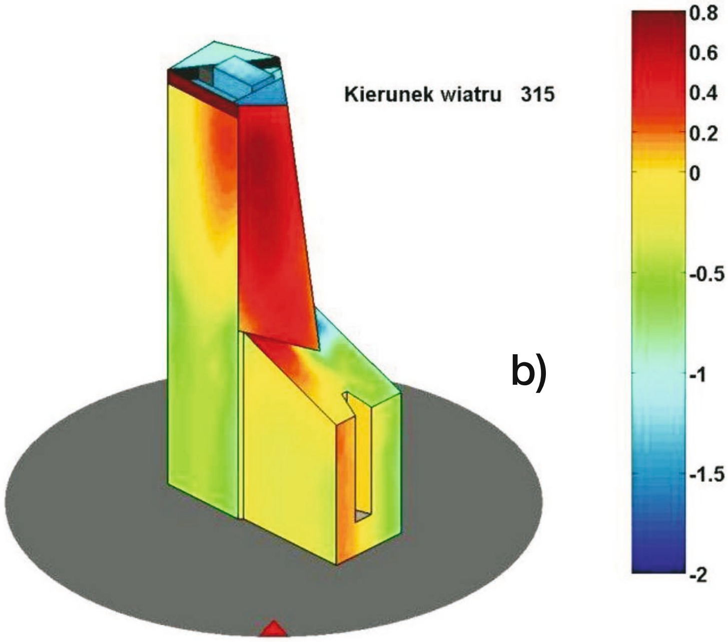
Fig. 4.a–f. Q22 Office Building, Warsaw, APA Kuryłowicz. Source: photo by the author (2023)

3.3. Case study: q22 high-rise building, Warsaw (2017)

Fig. 5a–b. Building model and the surrounding environment in the measurement space of the wind tunnel. Visualization of the distribution of the average wind pressure coefficient on the external surface; source: A. Flaga 2015, Laboratory of Wind Engineering, Cracow Univ. of Tech. 2013

Q22 skyscraper in Warsaw was designed by the leading Polish architectural office Kuryłowicz and Associates. This 155 m tall high rise office building was built in 2017 (Fig. 4a–f). Buro Happold was appointed to provide building services engineering as well as BREEAM assessment and consulting for this project. Model tests and study analyses of the impact of wind on the tall building were carried out by the team of prof. A. Flaga at the Wind Engineering Laboratory of the Cracow University of Technology in 2013 (Fig. 5a–b.) [A. Flaga 2015].

The building has a unique asymmetric shape designed to resemble a quartz crystal. The irregular shape coupled with the fact that the structural core had to be shifted away from the center, demanded rigorous design supported by wind tunnel and CFD simulation. Sustainable objectives also informed the building's solutions incorporating a number of innovative techniques including tri-glass facade, which give better thermal and acoustic isolation, minimizing the building's heat loss during the winter and solar gains during the sum-



mer. Thermal and lighting zoning further reduce power consumption. To capture solar energy, a photovoltaic system was incorporated into the design of the sloping glass roof. This generates renewable energy which can be used to power the charging points for electric vehicles. Sustainable objectives also informed the building's heating, ventilation and air conditioning design. Using air-water heat pumps, energy is recovered from the server and technical rooms and redistributed around the building, providing significant energy savings.

According to Mycielski: "*The designers of Q22 did not have an easy task also because the skyscraper, built among blocks of flats from the 1960s, was subject to numerous restrictions related to the need to ensure access of light to single-sided apartments located in neighboring buildings. The architects treated these difficulties as an excuse to shape the structure and turned it into an advantage. Analyzing the impact on the neighborhood and controlling the effect on the urban model, the skyscraper was bent, tilted and carved with cuts, while simultaneously improving its slenderness on all sides. At the same time, the transparent and minimalist character of the architecture has not been lost*" [K. Mycielski 2017].

3.4. Wind analysis results

Windflow analysis performed in Autodesk Flow Design make it possible to reverse engineer two different form optimization strategies used by the architects who designed the buildings. The results are presented in Tab. 3.

The analysis of case studies was carried out using Autodesk Flow Design software according to the methodology mentioned earlier. Both analyzed buildings are located in a dense urban environment. Neither of the analyzed buildings was the first obstacle to the incoming air from the west. As a result of simulation tests, the distribution of wind speed and pressure around the building was obtained. The air flow determined by the building arrangement also plays an important role in the convection and evaporation processes occurring both on the outer surface of the partitions and in their near-surface zones.

The analysis revealed a relatively high influence of designed forms and their aerodynamic interference with neighboring buildings, including the occurrence of:

- local changes to average wind speed for each wind direction,
- aerodynamic couplings: airflows, vertices,
- differences in pressure pattern distribution,
- vertical airflows,
- near-façade wind flow pattern and surface pressures patterns.

Direct outcomes include horizontal and vertical pressure variations resulting in dynamic movement of air masses sideways, upwards and downwards with increased speed. The aim of the analysis was to monitor and limit unfavorable phenomena such as excessive local accelerations of air masses and wind impacts resulting from turbulence. As a result of simulation tests, the wind speed distribution around the building was obtained.

Tab. 3. Form optimization strategies

BUILDING NAME	BUILDING HEIGHT	WIND ANALYSIS METHOD USED BY ARCHITECTS	FORM OPTIMIZATION STRATEGY
PLAC UNII HIGH-RISE BUILDING	90 m	Scale model	Triangular plan Edge filleting
Q22 HIGH-RISE BUILDING	155 m	Scale model CFD	Form-finding of aerodynamic shape

Source: prepared by the author

The architectural forms of the two high-rise buildings were assessed in terms of features determining the occurrence of aerodynamic phenomena for prevailing western winds with a speed of 25 m/s at an altitude of 40 m. In order to illustrate the effect of wind on heat loss, a numerical CFD analysis was performed around the high-rise buildings. The study shows airflow effects on the two high-rise buildings located in a dense urban area of Warsaw: Plac Unii complex (Fig. 6a–c) and Q22 building (Fig. 7a–c).

The ease of use makes Autodesk Flow Design available not just to traditional users (mainly in aerospace and automotive industry) but also for architects. Flow Design provides easy input of 3D data into their software from many sources. Simplified CFD solver that simulates airflow with rather low detection of weather anomalies and seasonal patterns is an obvious disadvantage, however Flow Design has demonstrated its ability to give information about:

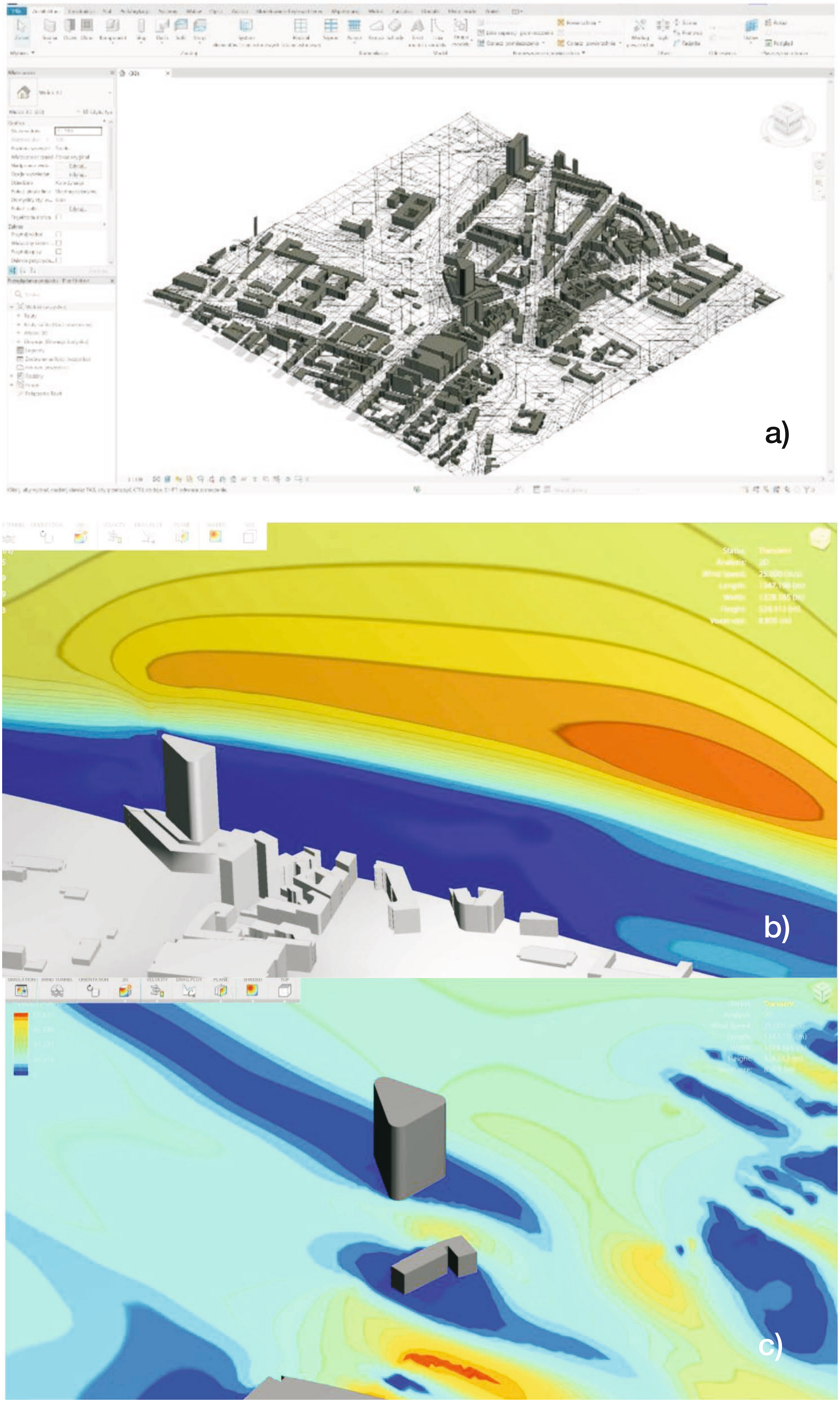
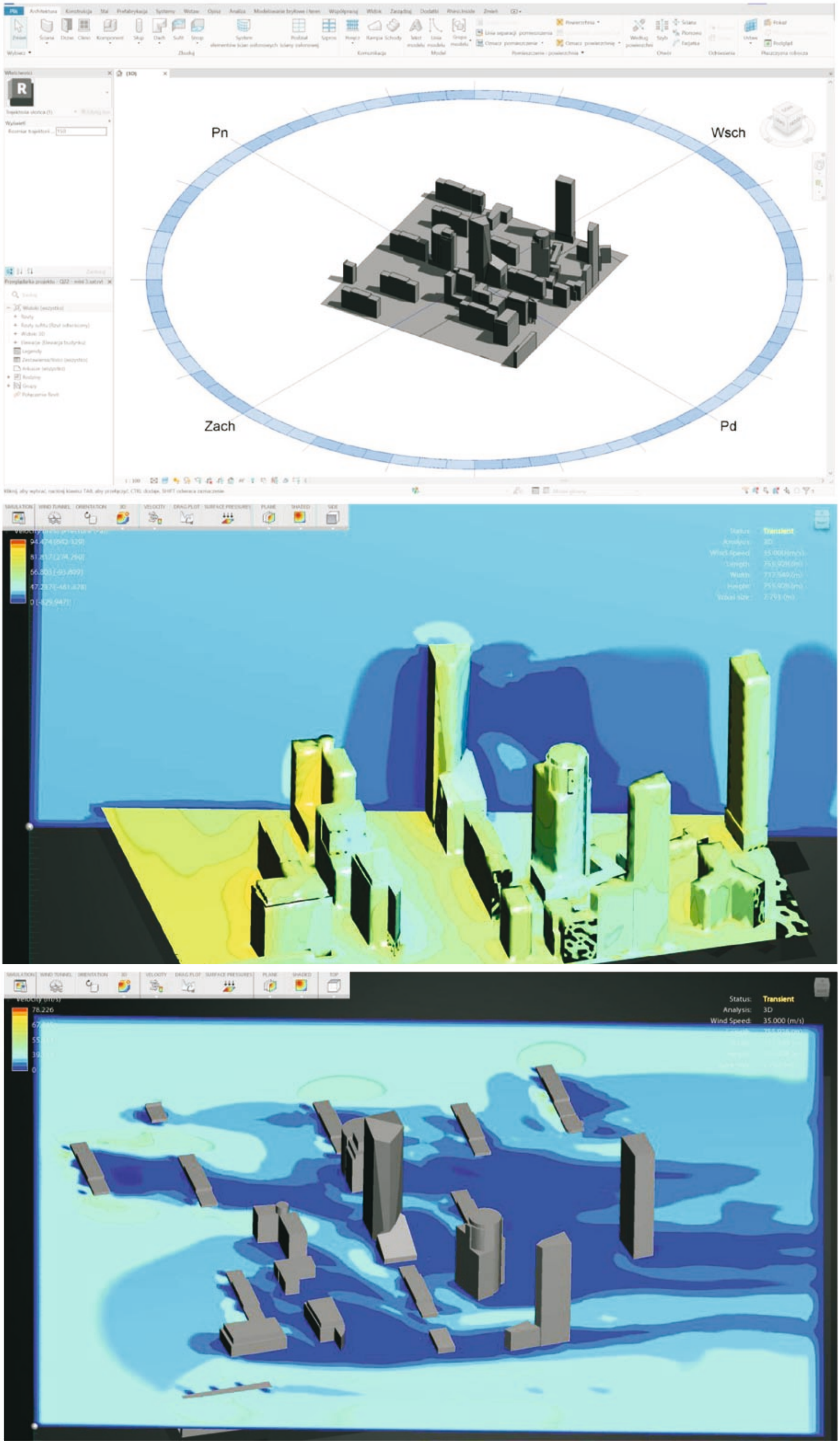


Fig. 6a–c. Plac Unii building CFD analysis (prevailing western wind speed: 25 m/s at an altitude of 40 m) a) 3D model of Union of Lublin square (plac Unii Lubelskiej), b) vertical velocity profile and surface pressure, c) horizontal velocity profile; source: by the author (2023)



a)

b)

c)

Fig. Fig.7a–c. Q22 building CFD analysis (prevailing western wind speed: 25 m/s at an altitude of 40 m)
a) Revit 3D model, b) vertical velocity profile and surface pressure, c) horizontal velocity profile;
source: by the author

- Potential for natural ventilation through various wind speed and pressures inside and outside the building,
- Wind hindrance at certain areas around the building, where wind speeds are too high,
- Renewable energy generation by optimizing the form of the building to harness wind energy.

CONCLUSIONS

Architectural design should aim at creating forms shaped to enable natural air circulation inside and around buildings. Modeling airflow, atmospheric phenomena and weather anomalies has an increasingly visible impact on the architectural form-finding process of a building that can be modeled both physically and virtually. The analysis results can also be used as input data for energy analyses when determining changes in the heat transfer caused by the impact of wind. Analysis can also be performed of pressure differences and aerodynamic phenomena of stagnations and vortices that can accumulate air pollution and play an important role in the convection and evaporation processes occurring both on the outer surface of the partitions and in their near-surface zones.

Application of CFD analysis tools in architectural design is crucial to counter the effects of climate change. Wind analysis accurately accounts for various project specific factors that include: aerodynamic influences associated with building shape, directionality of wind associated with regional wind climate and influence of neighboring buildings and land topography. Both physical wind tunnels and Computer Fluid Dynamics methodology provide the essential tools to examine airflow patterns. The dynamic model is used to simulate and model the behavior of both inner and external volumes of the building. It includes anomalies in weather model patterns and unexpected occurrences. Wind engineering is a combination of art and science, and it is important for architects to understand aerodynamics of buildings, therefore windflow analysis performed by CFD tools is worth implementing in academic curriculum.

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