pages: 33 - 48

APPLICATION OF CFD ANALYTICAL TOOLS IN ARCHITECTURAL DESIGN IN THE CONTEXT OF WIND LOADS – PART 1

Justyna Juchimiuk

University of Zielona Góra, Construction Department, Architecture and Environmental Engineering, ul. Prof. Z. Szafrana 1, 65-516 Zielona Góra, Poland
E-mail: j.juchimiuk@aiu.uz.zgora.pl, ORCID: 0000-0003-2934-2349

DOI: 10.24427/aea-2023-vol15-11

Abstract
The article discusses the impact of air flow on architectural form. Climate change related extreme weather events expected in the near future pose a significant challenge and require the integration of building aerodynamics in the architectural design process. Windage analyses carried out at an early design stage are an essential tool in the process of searching for the architectural form of buildings designed to resist extreme wind events.
Due to the breadth of the topic and the limitations of the article's length, the text has been divided into two parts. The first part of the article presents early concepts of building aerodynamics, historical methods of wind flow analysis based on observations and physical models, as well as the use of CFD (Computational Fluid Dynamics) analytical tools. The article reviews and compares three wind analysis tools based on the CFD methodology: Autodesk CFD, Autodesk Flow Design and Butterfly (Ladybug plug-in). The results of an original study of the aerodynamics of the building of the high-mountain meteorological observatory on Śnieżka using the Autodesk Flow Design software were also presented as a case study of a facility located in extreme weather conditions and designed with a clear reference to aerodynamics. The second part of the article discusses the methodology of research on the aerodynamics of high-rise buildings and the impact of wind load on the architectural form of buildings. Case studies of two high-rise buildings located in Warsaw, made using the Autodesk Flow Design program, were also presented.

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

INTRODUCTION

Computational Fluid Dynamics (CFD) is a tool for analyzing fluid-flow problems with various numerical methods that convert the partial different equations that govern a physical phenomenon into a system of algebraic equations. CFD analysis can be performed on either physical models or simulations. When this is done on physical models, CFD software analyzes the airflow around the model and predicts what will happen when the air interacts with the object under study. When CFD analysis is performed on simulations, the CFD software analyzes the airflow over an object that has been created in a computer simulation program. The next step in the CFD analysis and simulation process is to generate a mesh. CFD software creates a mesh of the test object. It can then be used to calculate some of the airflow properties around the test object. On this basis, the software in which the CFD simulation is performed analyzes the particle data and generates 3D visualizations. The final step in CFD analysis is to analyze the particle data and generate 3D visualization data. This data allows you to see how air flows over and into the object. The purpose of conducting this type of analysis is to help choose the best facility design.

Globally, the building sector is the source of approximately 40% of total energy consumption. According to United Nations Framework Convention on Climate Change long-term shifts in temperatures and weather patterns are attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time, in particular for temperature extremes.

Climate change has a significant impact on the built environment and architects and designers must consider these consequences. The frequency and intensity of extreme weather (including storms, cyclones, heatwaves) have increased. As members of the Committee on Extreme Weather Events and Climate Change state: "*The observed frequency, intensity, and duration of some extreme weather events have been changing as the climate system has warmed. Such changes in extreme weather events also have been simulated in climate models, and some of the reasons for them are well understood. For example, warming is expected to increase the likelihood of extremely hot days and warming also is expected to lead to more evaporation that may exacerbate droughts and increased atmospheric moisture that can increase the frequency of heavy rainfall and snowfall events.*" [National Academies of Sciences, Engineering, and Medicine 2016].

1. IMPACT OF AIRFLOW ON ARCHITECTURAL AND URBAN DESIGN

Designing comfortable buildings has been a goal of architects since the writings of Marcus Vitruvius Pollio and Leon Batista Alberti. Vitruvius, a Roman architect and engineer during the 1st century BC, known for his multi-volume work titled *De architectura* had a simplistic view of winds, regarding all as undesirable (Fig. 1a–b). Vitruvius regarded all winds as deleterious to health: *"if the winds are cold they damage the health, if hot, they are infectious, and if humid, they are noxious"* [A. Nova 2006]. He argued for their complete exclusion: "*Excluding the winds will not only make a place healthy for people who are well, but also…* [diseases] *will be cured more rapidly in these areas because of the moderate climate created by the exclusion of winds*" [A. Nova 2006]. Vitruvius concern with winds makes sense given that window glass wasn't widespread at the time. The ancient Romans were the first known to use glass for windows, but the technology was first produced in Roman Egypt, in Alexandria around c. 100 AD.

Vitruvius described wind distribution in a diagram of eight-sided wind rose. The diagram was not used to map the directions of the predominant winds, because Vitruvius did not recognize that different locations for cities might have different prevailing winds. Rather, he thought that the winds could come only from these eight directions and, for a given location, from any and all of them at various times (Fig. 1a). This eight-wind logic suggested to Vitruvius that orienting the street grid in a city 'between' these eight directions, no matter where the city was located, could ensure that the inhabitants were not unduly exposed to the winds: "*For these reasons, the rows of houses should be aligned away from the directions in which the winds blow, so that when they arrive, they buffet the corners of the blocks of houses and so are repelled and dissipate themselves*" (Fig. 1b) [A. Nova 2006].

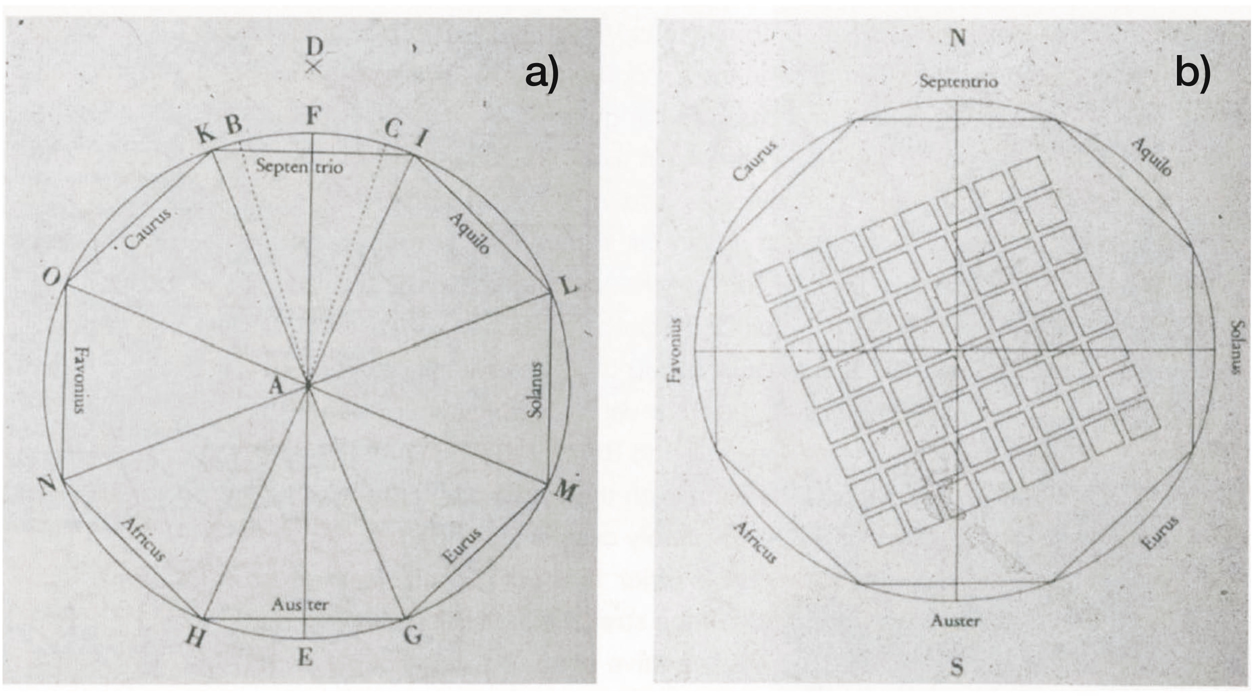


Fig. 1a–b. Wind engineering according to Vitruvius, a) reconstruction of the "scheme" of the major wind, b) reconstruction of the orientation of the city's urban plan in relation to the blowing winds; source: A. Nova 2006

In book 1 of *De Re Aedificatoria* (*On the Art of Building*) the Italian renaissance architect Leon Battista Alberti defines buildings as consisting of *lineaments* and *matter* – design and matter. Alberti viewed the idea of *lineaments* not only with regard to architecture but also as a property of a living body. Alberti writes, of the comparison between the body of a fish and a ship's form: "*If these 'lineaments' were laid out correctly, with the proper flaring and tapering from bow to stern, the ship would indeed be fish-like, moving through the waters as if of its own accord*". They can also be seen as an essential vivifying characteristics of that body, qualities of motion and experience particular to that body. Due to this the idea *lineaments* is performative, not just an aesthetic one. In Alberti's view that *lineaments* are an essential characteristic of living bodies, there is the implication that if the *lineaments* of the artificially constructed objects is done correctly, they could possess the qualities of life itself. *Lineaments* seem to describe the essence of life as it relates to matter itself rather than any aesthetically-oriented codification of proportions. Buildings should therefore be constructed with regards to the site, sun, and wind. Elements such as walls and roofs as well as openings have an imperative to protect against weather while also allowing for light and ventilation. Alberti recognizes the limitations that the forces of nature impose on builders. Among the elements, he considers air to be the most powerful: "*If the Earth or Water had any defect in them, Art and Industry might correct it; but neither contrivance nor multitude of hands was able sufficiently to correct and amend the Air*" [A. Nova 2006]. For Alberti as he stated in his treaty the wind is incredibly important in decision making: from the temperatures it brings, the strength it carries, the direction it has etc.

Alberti's interests in atmospheric phenomena included scientific aspects. It's worth noting that the Italian architect invented the first mechanical anemometer in 1450. This instrument consisted of a disk placed perpendicular to the wind. It would rotate by the force of the wind, and by the angle of inclination of the disk the wind force momentary showed itself. The same type of anemometer was later re-invented by Englishman Robert Hooke [A. Nova 2006].

2. AERODYNAMIC MODELING IN ARCHITECTURAL DESIGN

Building aerodynamics 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 The research of building aerodynamics deals with the investigation of flow processes in the atmospheric layer, with emphasis on the analysis of wind flow within the influence area of buildings and to the resulting wind loads on buildings and structures. The study of the wind comfort and pollutant dispersion in urban areas is also taken under considerations of building aerodynamics including urban landscape, static and dynamic wind loads, pedestrian comfort, and ventilation. The word aerodynamics combines 'aero' meaning air, atmosphere or gases, from the Greek *aero* or lower atmosphere and 'dynamic', relating to mechanical forces not in equilibrium from the Greek *dynamikos* meaning powerful. Aerodynamics have been a consideration in the construction of sailing boats and windmills for many years, whilst aerodynamic concepts date back to Aristotle and Archimedes in the 2nd and 3rd centuries BC. Sir Isaac Newton was the first to develop a theory of air resistance in the early 1700's, expanded some years later in *Hydrodynamica* which describes the relationships between pressure, density, and flow velocity, known as Bernoulli's principle after its author, it also provides a method to calculate aerodynamic lift [Designing Buildings 2022].

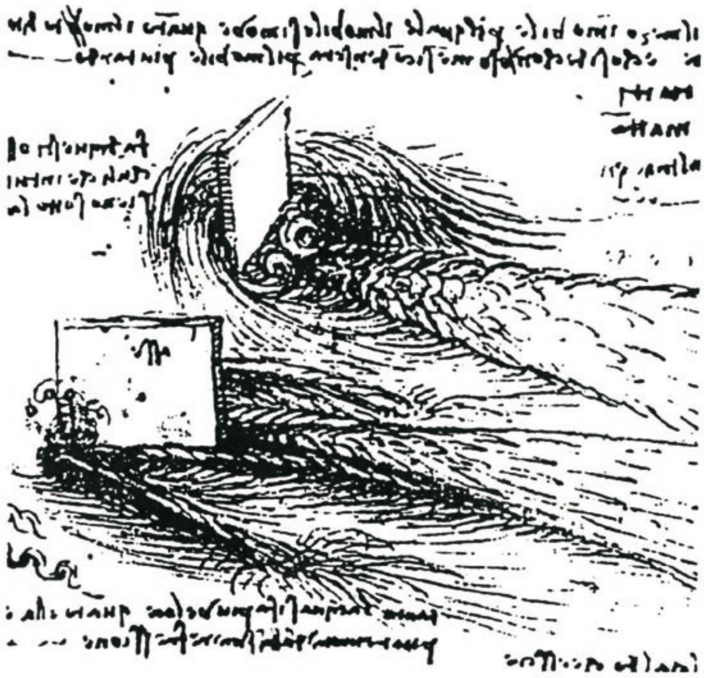


Fig. 2. Leonardo Da Vinci, Flowlines and flowplanes found in the Codex Atlanticus; source: J.D. Anderson Jr. 2008

In addition to this quantitative contribution to an amazingly broad variety of subjects Leonardo Da Vinci was a consummate observer of nature. His sketches of various flowlines and flowfields are significant examples of Leonardo's awareness of complex aerodynamics.

The drawings demonstrate an experiment either physical or conceptual of a flat plate washed by streams of gas or liquid (Fig. 2). His assumptions of vortex structure of the flow around blocking objects are amazingly accurate in the light of modern scientific research. As J.D. Anderson notices: "*At the top, the plate is perpendicular to the flow, and Leonardo accurately sketches the recirculating, separated flow at the back of the plate, along with the extensive wake that trails downstream. At the bottom, the plate is aligned with the flow, and we see the vortex that is created at the junction of the plate surface and the water surface, as well as the bow wave that propagates at an angle away from the plate surface. These sketches by Leonardo are virtually identical to photographs of such flows that can be taken in any modern fluid dynamic laboratory, and they demonstrate the detail to which Leonardo observed various flow patterns.*" [J.D. Anderson Jr. 2008].

2.1. Wind tunnel testing

Since its beginnings in the XIX century wind loading effects were determined by wind tunnel tests. Wind tunnels are vitally important tools for aerodynamics research in many areas of technology. They are used to test the aerodynamic effects of aircraft, rockets, cars, and buildings. Wind tunnels are usually technical test devices where an object is held stationary inside a tube, and air is blown around it to study the interaction between the object and the moving air. The first wind tunnel of this kind in the world was built and tested in 1871 by Frank Wenham. The Wright Brothers used a tunnel as an aid in the design of the Wright Flyer (Fig. 3).

In the 1930's, pioneer wind tunnel tests were performed by Danish wind engineers J.O.V. Irminger and C. Nokkentved, who investigated the nature of air movement over buildings, in particular the accuracy of wind-tunnel methods for reproducing the correct air-flow separation and reattachment positions of the vortices formed by winds passing over buildings (Fig. 4a–b.). The experiment shed light on the importance of suction on the overall wind loading [G.L. Larosea, N. Franck 1997].

Fig. 3. Replica of the Wright Brothers' wind tunnel at the Virginia Air & Space Museum in Hampton, VA; source: photo by Erik Axdahl, licensed under the Creative Commons Attribution-Share Alike 2.5 Generic license 2006

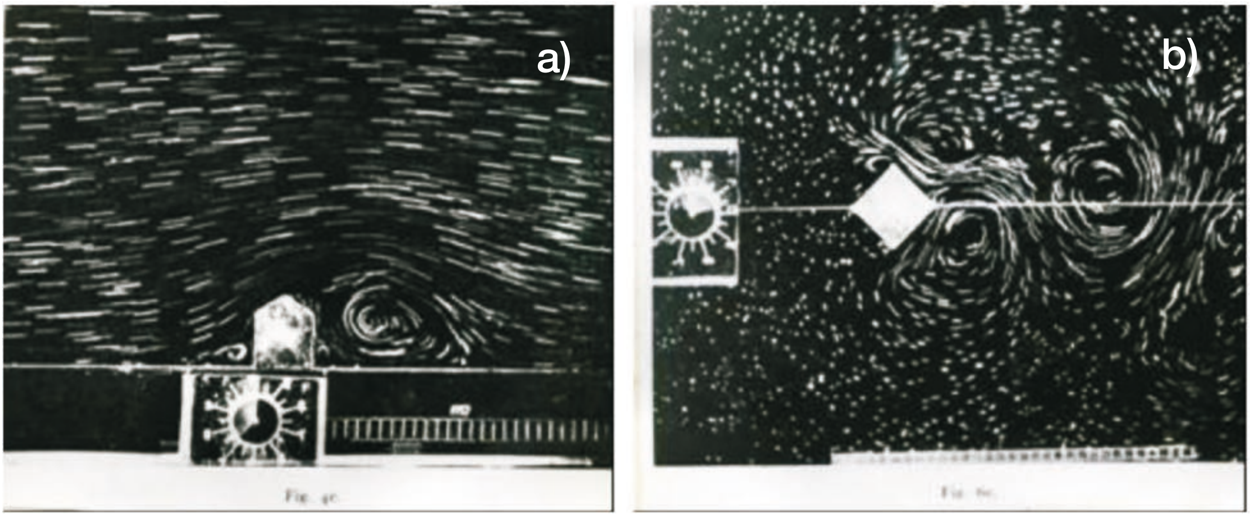


Fig. 4a–b. Early wind tunnel experiments on wind loads on structures by J.O.V. Irminger and C. Nokkentved; source: C.P.W. Geurts 2005

Wind tunnels are used in many engineering and environmental applications as a key tool in understanding the problem associated with the aerodynamics and transport phenomenon. The dispersion of pollutants over industrial and residential areas, the impact of lift and drag on various structures and wind load on civil installation are examples where wind tunnel simulation can be used to understand and control the related problem.

The typical issues for which a wind tunnel test might be commissioned for a building include life safety issues of accurate determination of local pressures and wind-induced structural loads and responses. Also, typical serviceability issues of pedestrian wind conditions, building exhaust dispersion that contribute to the public and occupant perception of the quality of the built environment and fire safety issues are of concern. As wind tunnel testing relies on physical testing incorporating the particular site conditions, unnecessary over design is avoided. Wind tunnel testing accurately accounts for various project specific factors which affect the results and can be modelled in detail. Typical factors may include but are not limited to the following:

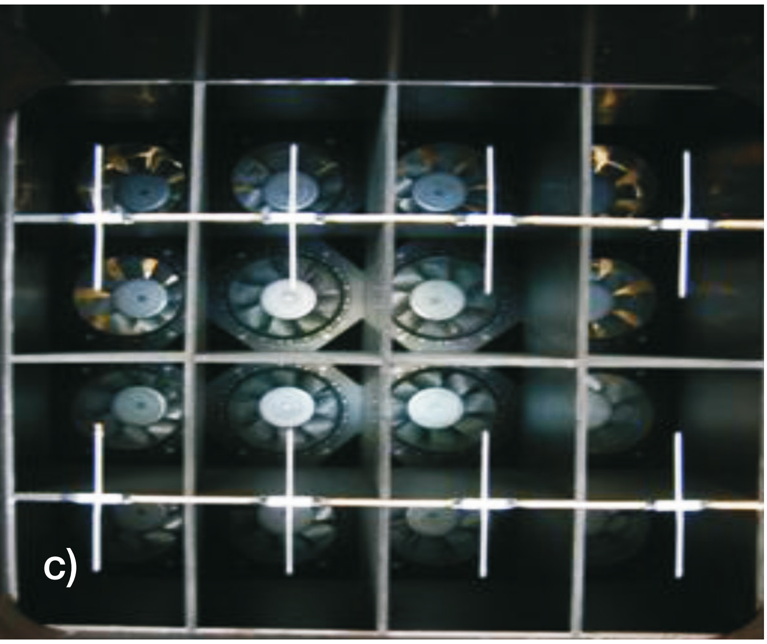
- Aerodynamic influences associated with building shape.
- Directionality of wind associated with regional wind climate.
- Influence of neighboring buildings and land topography.
- Interaction between building motion and wind flow.

KEZO PAN - Wind Energy Laboratory, Jabłonna, Poland

KEZO Research Center of the Polish Academy of Sciences Energy Conversion and Renewable Sources is a branch of the Institute of Fluid-Flow Machinery located in Jabłonna near Warsaw. The center is the most modern complex of research laboratories in Poland dealing with the use of renewable energy. The main scientific tasks, which also constitute the research basis of the Institute of Fluid-Flow Machinery, focus on the conversion of energy from renewable sources in research fields closely related to the country's energy security. The basic task of the Center is to conduct research on energy from renewable sources and its conversion.

The wind energy laboratory has an open low-speed wind tunnel equipped with two independent measurement chambers, one of which is adapted for model testing. The tunnel operates in suction mode and reaches a flow speed in the measuring chamber of up to 30 m/s. The measuring chamber is 4 meters long and has a square cross-section of 2 meters by 2 meters (Fig. 5a–g). The tunnel measuring chamber is equipped with the following measuring systems:

- velocity field measurement – sliding row of thermo-anemometric sensors,
- forces and moments – Stewart platform with optical strain gauge,
- deformations – a system of optical measurement of deformation of elements under the influence of aerodynamic forces,
- noise – portable acoustic camera to measure the intensity and location of the noise source.



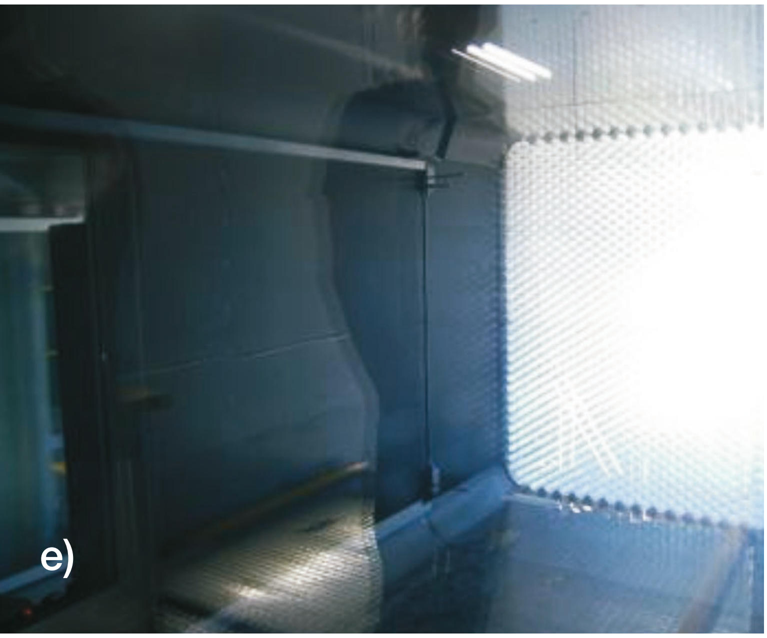
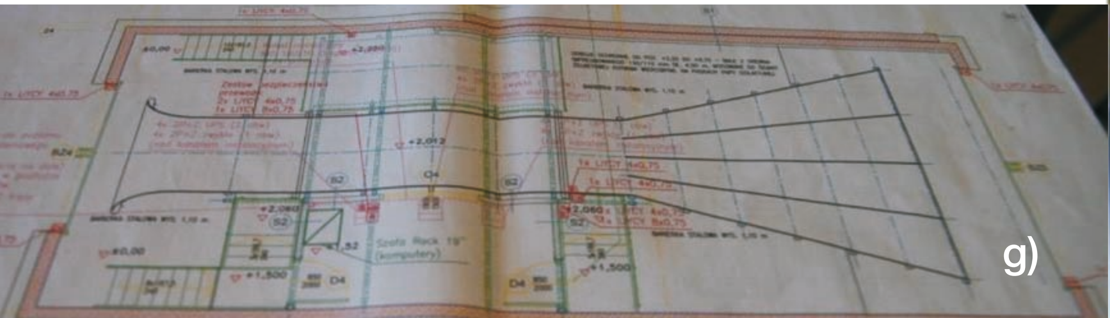


Fig. 5a–g. PAS Research Centre, Energy Conversionand Renewable Resources KEZO, Jabłonna near Warsaw, Poland a) buildings B2,B2/1 and Laboratory of Wind Energy L3, b–g) is provided an open flow low speed wind tunnel designed to testing small scaled wind turbine (equipped with an open low-speed wind tunnel that is equipped with two independent measurement chambers; required for testing small wind turbines or models). KEZO can also realize numerical simulations supporting analysis and design of wind turbine and investigations of other wind energy related issues; source: photo by the author 2019



Wind Engineering Laboratory, Krakow University of Technology, Poland

Wind Engineering Laboratory of the Krakow University of Technology, headed by prof. Andrzej Flaga is the only scientific and research center in Poland that carries out tests of buildings. Simulation tests of snow load on the roofs of the main and training halls are carried out in the laboratory's wind tunnel (Fig. 6a–b). They are used to determine the data necessary for static and strength calculations of the structures of both halls. This is necessary for the safety of the structure. The research also serves to verify the assumptions made in the construction design and to indicate possible savings in terms of reducing the weight of the main supporting steel structure of the roofs of both halls.

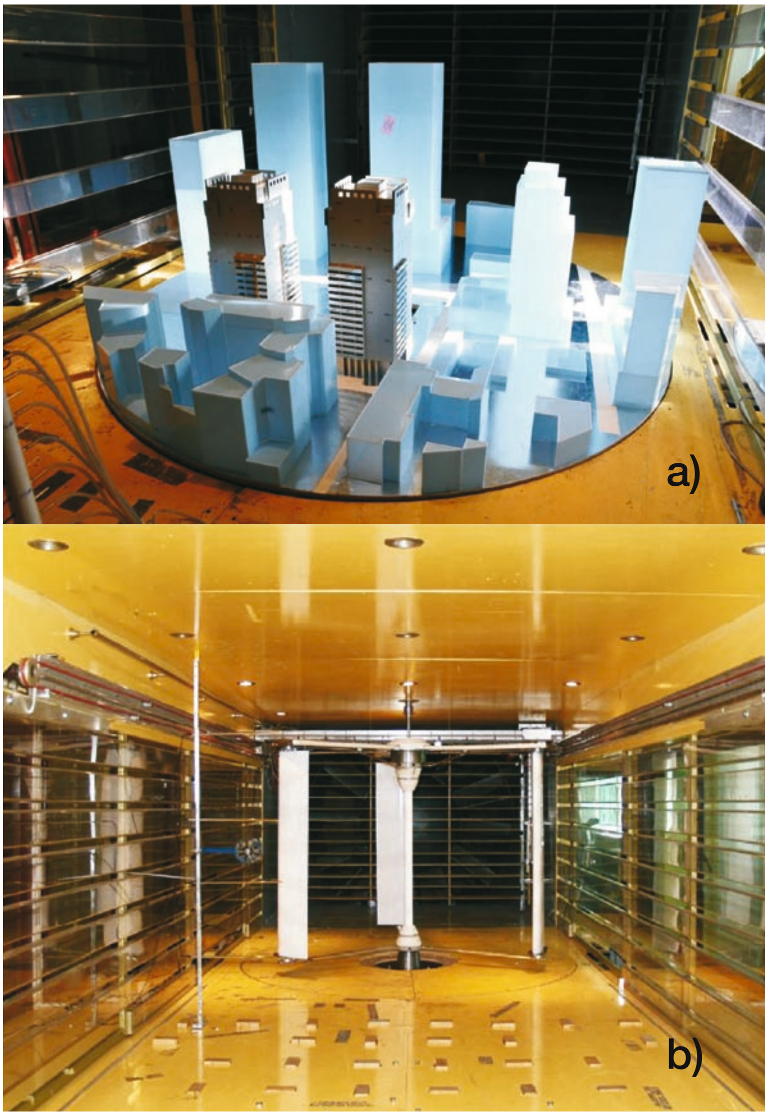


Fig. 6a–b. Wind Engineering Laboratory of the Krakow University of Technology; source: A. Flaga 2015

2.2. Computational fluid dynamics modeling

The pioneering application of CFD analysis in architectural design in the 1990s were presented by Branko Kolarevic: ***"****Future Systems, a design firm from London, used the computational fluid dynamics (CFD) analysis in a particularly interesting fashion in its Project ZED, the design of a multiple-use building in London (1995). The building was meant to be self-sufficient in terms of its energy needs by incorporating photovoltaic cells in the louvers and a giant wind turbine placed in a huge hole in its center. The curved form of the façade was thus designed to minimize the impact of the wind at the building's perimeter and to channel it towards the turbine at the center. The CFD analysis was essential in determining the optimal performance of the building envelope.*" [B. Kolarevic 2003].

CFD has many advantages. It can be used in conjunction with other engineering disciplines. Besides, engineering calculations using CFD calculation software are more accurate than manual engineering calculations. This is due to the use of a computer-generated, virtual numerical model and computational fluid dynamics software, which uses these models to calculate many variables, as well as the forces acting on each part of the object. The most popular type of CFD analysis is the calculation of pressure and velocity potentials on the surface of an object. This allows for accurate prediction of the forces acting on an object by applying Newton's laws of motion. The equations used for this analysis are described as a boundary condition to obtain accurate predictions. Boundary conditions can be set to calculate the forces and moments acting on individual points on an object.

Over the past 40 years, a wide variety of computational software programs and models have constantly worked on maximizing the accuracy of their tools to simulate and measure the impact of climate on the effectiveness of urban environments. Popular CFD software tools in architectural design are Autodesk CFD, Autodesk Flow Design, Butterfly (Ladybug Tools).

- **Autodesk CFD** is professional stand-alone software for Design Studies. This fluid flow and thermal simulation tool helps to predict product performance, optimize designs, and validate product behavior including thermal prototyping, architectural and MEP tools, and flexible cloud solving options. It also minimizes reliance on costly physical prototypes. Besides, it enables users to easily explore and compare design alternatives to better understand the implications of design choices using an innovative Design Study Environment and automation tools. A design Study conducted in Autodesk CFD contains a single analysis called a Scenario, where the materials (fluids, solids, devices), boundary conditions (velocity, flow rates, temperatures), and the mesh element size are defined [Autodesk Support 2023]. Using multiple design variants in a study reveals the effects of geometry modifications on airflow inside and outside the building. Comparative analysis method of the results is incredibly valuable while developing new design strategies. Autodesk CFD supports direct data exchange with most CAD software tools, including Autodesk Inventor, Autodesk Revit, Graphisoft Archicad, Rhino and Sketchup software.

- **Autodesk Flow Design** is a discontinued standalone application that simulates wind interactions with a building volume developed by Autodesk Labs in 2014-2018. Its successor Autodesk CFD (2019–2024) is the high-end, multipurpose Computational Fluid Dynamics software package dedicated to professional design engineers and analysts [Autodesk Support 2023]. Flow Design is a CFD standalone application limited in its functionality, control, and accuracy. This purpose built wind tunnel simulator models wind behavior around an exterior and provides an understanding of where there may be risks of elevated wind speeds or where there may be stagnant areas that affect air quality or comfort. The product itself shares many similarities with other Computational Fluid Dynamics (CFD) applications. Instead of solver based on the conditions that gives a solution that matches with seasoned fluid mechanics and meteorological data Autodesk Flow Design uses its native Fluid Dynamics solver based on earlier Project Falcon developed by Autodesk Labs in 2013.
- **Butterfly plugin** is a Ladybug tool and a python library to create and run advanced computational fluid dynamic (CFD) simulations using OpenFOAM, which is one the most rigorously-validated open source CFD engines in existence and is capable of running several advanced simulations and turbulence models (from simple RAS to intensive LES). Butterfly is built to quickly export geometry to OpenFOAM and run several common types of airflow simulations that are useful to building design. This includes outdoor simulations to model urban wind patterns, indoor buoyancy-driven simulations to model thermal comfort and ventilation effectiveness, and much more [Ladybug Tools LLC 2023]. The Butterfly can also simulate CFD-based models in noticeably less time compared to the other models. These capabilities qualify the Ladybug tools to be one of the most efficient CFD tools for architects when it comes to optimization studies and time and resource efficiency.

Ladybug tools are embedded in the Grasshopper interface for Rhino3D and have the parametric abilities of the Grasshopper which is a script-based modeling algorithm. Visual programming language interface allows designers to create geometries and environments manipulating various design parameters and recreating different geometry configurations through geometrical iteration. The Ladybug tools comprise Ladybug, Honeybee, Butterfly, and Dragonfly plugins. Each has its own capabilities that specialize in a particular field and analyze certain factors, and they could also integrate to fulfill further analysis requirements. This potential allows Ladybug tools to simulate numerous geometry configurations as well as measure, evaluate, and optimize their performance throughout the year, as opposed to other models, which can handle a limited number of urban canyon geometries to be able to optimize them. Each of the Ladybug tools basic functionalities have been presented on Tab. 1.

Tab.1. Ladybug tools and their basic functionalities

Ladybug tools A collection of open source computer applications that support environmental design and education	**Honeybee** Daylight and radiation analysis using Radiance software and energy models using EnergyPlus or Open Studio software
Butterfly Advanced Computational Fluid Dynamics (CFD) using OpenFOAM software	**Dragonfly** Analysis of large-scale factors such as district-scale energy models for energy simulation with the URBANopt analytics platform and renewables optimization with the REopt energy planning platform

Source: prepared by the author

Tab. 2. Presents a comprehensive review of CFD analytical tools used in architectural and urban design

SOFTWARE NAME	SOFTWARE TYPE	LICENCE TYPE	CFD ANALYSIS DETAIL LEVEL	FLEXI-BILTY OF USE	USER-FRIENDLY INTERFACE	APPLICABILITY IN ARCHITECTURAL EDUCATION
Autodesk CFD	Stand-alone application	Trial Commercial	Mesh based comprehensive CFD Analysis	+	+/-	+/-
Autodesk Flow Design	Stand-alone application discontinued in 2019	Educational available in 2023	Voxel based simplified CFD Analysis	+/-	++	++
Butterfly (Ladybug Tools)	Plug-in application for Rhino-Grasshopper	Open-source	Mesh based comprehensive CFD Analysis	++	+/-	+

Source: prepared by the author

CFD analysis enables engineers to visualize, test, and analyze their product designs for problems concerning fluid flow, heat transfer, turbulence, etc. Alternative CFD tools comprise Ansys, SimScale, COMSOL, RayMan, CityComfort+, CitySim Pro. The main reasons behind using CFD tools in architectural design is:

- To validate design,
- To optimize design,
- Reduce reliance on physical testing,
- Accelerate project design and development.

Table 2 presents comparison of computer tools (programs, plug-ins and applications) available in architectural education. Three software tools: Autodesk CFD, Autodesk Flow Design, Butterfly (Ladybug Tools) were compared in terms of license type, CFD analysis detail level, flexibility of use, user-friendly interface, all resulting in their applicability in architectural education. All three tools can be used in the field of architectural design in research on environmental impacts of buildings on its surroundings as well as fields of civil and mechanical engineering, urban planning analysis & simulation in other scientific disciplines.

CFD meshing applies a numerical grid to a fluid body and boundary, similar to meshing in finite element simulations. Meshes are the input for computational fluid dynamics (CFD) analysis, whose size and quality have important impact on the simulation results. Voxel-based volume modeling and simplified meshing strategies enable interoperability between the domains of architectural design and building aerodynamics, as well as enable simple and rapid iteration of a particular conceptual design while maintaining a reduced level of mesh cells. With meshless CFD methods like Autodesk Flow Design and FFD (Fast Flow Dynamics) that improve the effectiveness of data computing, the analysis gains efficiency at the cost of simplifying the detail of the simulation. This increases efficiency without increasing the computing requirements, which is very important in education. The educational status of the discontinued Autodesk product combined with a user-friendly interface and fast voxel-based CFD solver makes Autodesk Flow Design a very valuable tool in architectural education.

3. APPLICATION OF CFD TOOLS IN ARCHITECTURAL DESIGN

J. Yao clearly stated that: "*Computational Fluid Dynamics (CFD) and physical wind tunnels have been applied in the field of flow simulation and analysis in many research papers. However, more accurate simulation results require higher-precision parameter settings and mesh grids that require more computation time from CFD software. If there is a series of buildings that need to be simulated, the experiment might be deemed impractically lengthy. Furthermore, the relationship between the wind and the building form through digital tools is highly complicated. On one hand, accurate simulation of fluids is a very com-plex process: modeling accuracy, fluid initial velocity, axial static pressure gradient settings, meshing, iteration steps and so on, will obviously influence the simulation results to a certain extent. On the other hand, the problem of interconnecting the CFD software to common architectural modeling software still needs to be resolved.*" [J. Yao et al. 2018].

Computer simulations such as CFD have opened up new possibilities for design and research by introducing environments in which we can manipulate and observe. However, using such simulation tools in a meaningful manner is not a straightforward or easy task. While visualization helped both parties – the architects and the engineers – in communicating and documenting the process, the meshing remained fairly time-consuming even for initial analysis of concept designs at the early stages of project development. As was noticed by S. Kaijima, R. Bouffanai and K. Willcox: "*Historically, most computational methods were developed based on structured meshes, which, in general, are generated effortlessly. This is particularly true when boundaries have a simply geometry. However, with the advent of more powerful computers, CFD practitioners started simulating more complex flows and geometries for which structured meshes are commonly computationally prohibitive. Unstructured meshes have gained popularity in recent years as an alternative approach for analyzing flow dynamics involving complex geometries*" (Fig. 10a–b) [S. Kaijima et al. 2013].

Case study - High Mountain Meteorological Observatory on Śnieżka

The High Mountain Meteorological Observatory on Śnieżka in Poland, designed by prof. Witold Lipiński in cooperation with prof. Waldemar Wawrzyniak (interiors) from Wrocław University of Science and Technology was chosen as a case study for wind analysis. This meteorological facility is undoubtedly the clearest example of Polish architecture with a clearly aerodynamic form. The observatory in the form of disks covered with aluminum sheet have become one of the symbols of the Karkonosze mountains. Autodesk Flow Design was chosen to perform a 2D computational fluid dynamics (CFD) numerical simulation considering different velocities and turbulences of air flows.

The method for simulating wind loads can be split into three discrete parts:

1. Site modeling using Cadmapper model of Śnieżka mountain and Autodesk Revit.
2. Case study building modeling using Autodesk Revit.
3. Simulating wind loads using Autodesk Flow.

Results obtained allowed to find a qualitative assessment of the contribution of architectural form on the wind flows in the area surrounding the building.

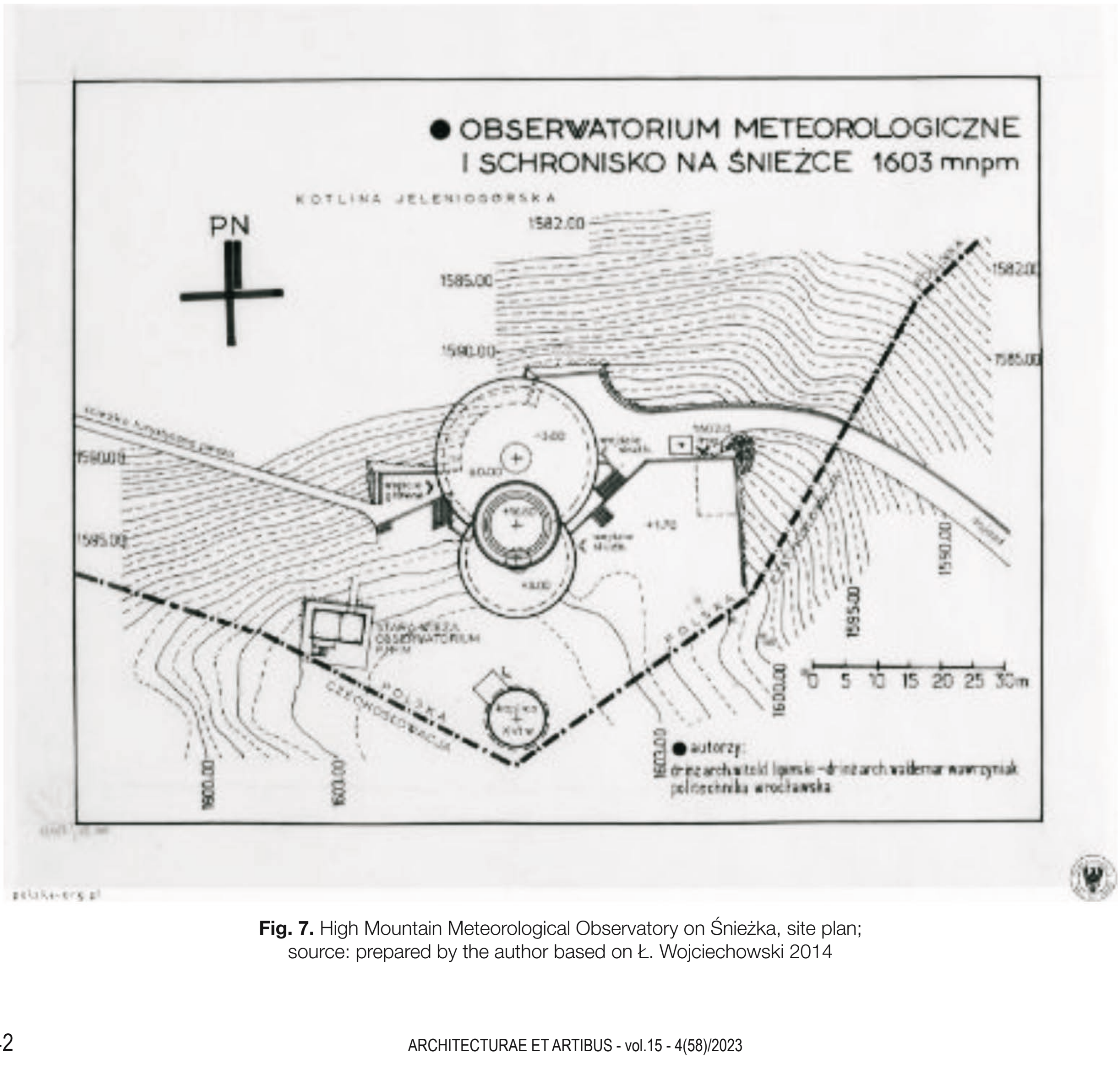


Fig. 7. High Mountain Meteorological Observatory on Śnieżka, site plan;
source: prepared by the author based on Ł. Wojciechowski 2014

Fig. 8 a–i. High Mountain Meteorological Observatory on Śnieżka – in the past and present: a), f) original drawings of Witold Lipiński and archival materials presented at the exhibition *Shape of Dreams – The Architecture of Witold Lipiński*; source: Museum of Architecture in Wrocław 2023, b-e) and g–i) Śnieżka 2022; source: J. Zych 2022

The observatory on Śnieżka, due to the uninterrupted meteorological measurement chain since 1880, is an ideal place to analyze climate change. These data are unique because the Śnieżka peak is devoid of local influences related to human activity. WOM Śnieżka is one of two Polish IMWM observatories included in the global system of high-mountain stations of the International Meteorological Organization (WMO), obliged to continuously conduct research and measurements. Architect Witold Lipiński who experimentally researched new technical solutions was in charge of design and project planning of the observatory. Before starting the design Lipiński performed a number of study flights above the peak of Śnieżka. His experience in gliding aviation gave him an intuitive approach to problems of building aerodynamics. This attitude is clear and evident in the design of the streamlined forms of the meteorological facility located in a difficult mountain climate. Lipiński also attached great importance to combining his works with the surrounding landscape.

The highest peak of the Karkonosze Mountains, Śnieżka, has been a popular hiking destination since the mid-19th century. In 1945, when the Polish administration took over the former German recreation infrastructure, the top of the mountain was relatively densely built-up – there were two shelters (one of them on the Czechoslovak side), a 17th-century chapel of St. Wawrzyniec and the meteorological observatory built in 1899. Due to the very poor technical condition of the wooden buildings, in the first half of the 1950s, preparatory work for the construction of a new facility was started, combining the functions of a shelter and a meteorological observatory. The first concept designs (Borys Lange and Czesław Sosnowski) assumed the construction of solid, cuboid forms with stone cladding.

The new observatory was supposed to be more than just an ordinary building replacing the over a hundred-year-old log structure in which meteorologists had previously worked. Therefore, the first concepts of a traditional rectangular shape were rejected by the investor and the project was commissioned to Witold Lipiński - then an assistant professor at the Faculty of Architecture, who was just starting to build his own house

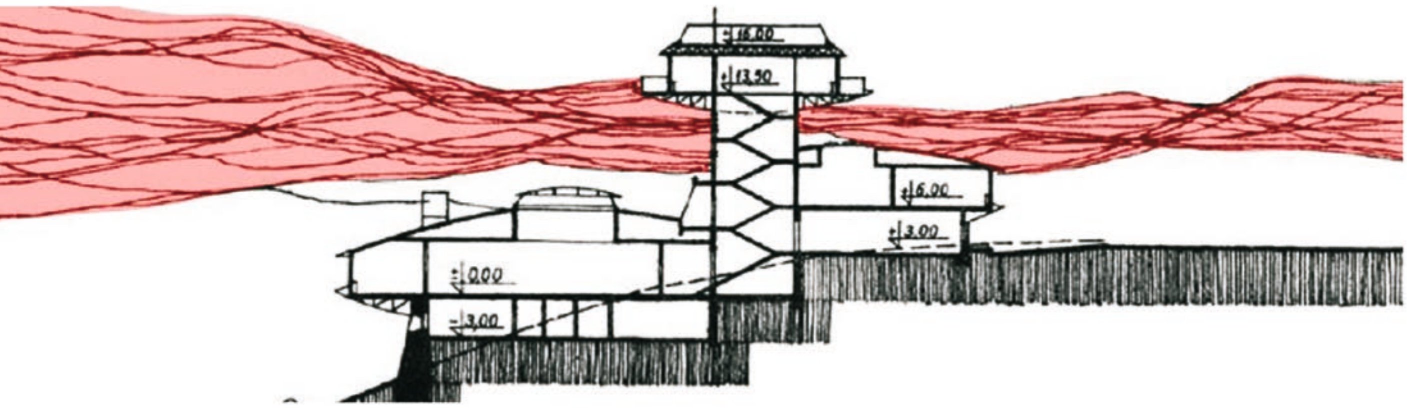


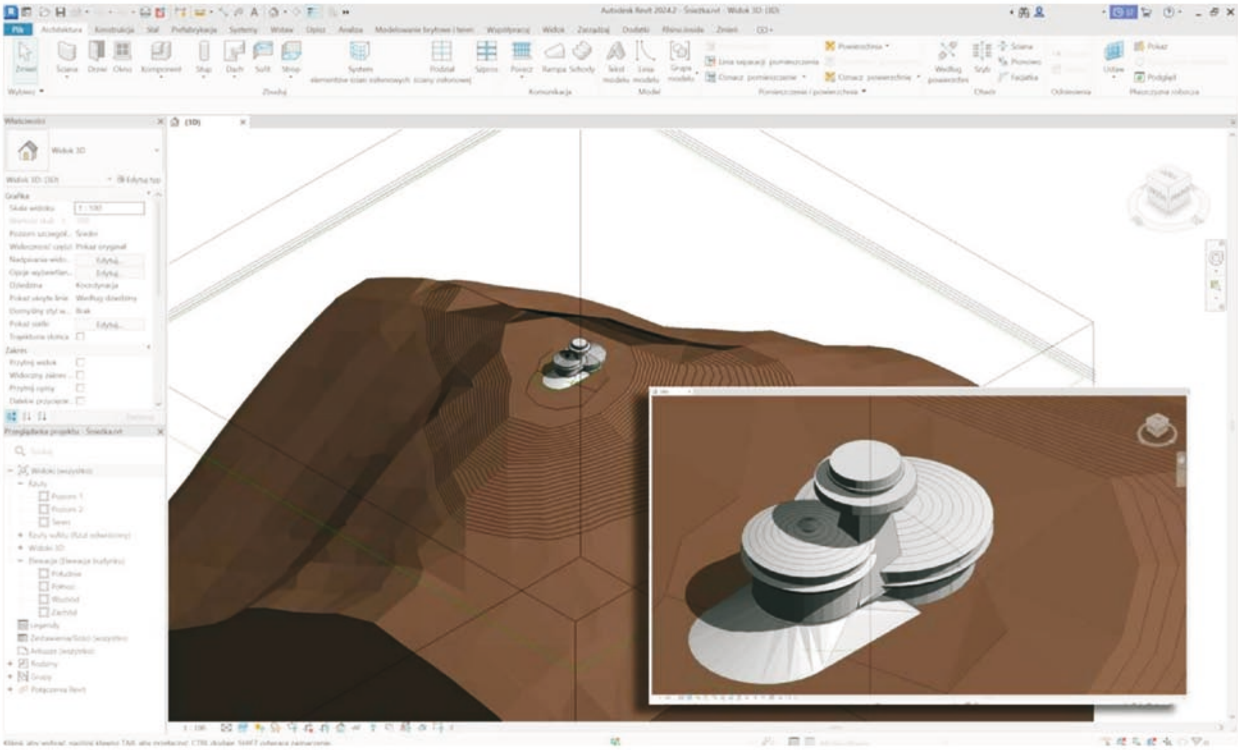
Fig. 9. Intuitive understanding of building aerodynamics, windflow marked on longitudinal section with highlighted airflow between discs of the High Mountain Meteorological Observatory on Śnieżka. Source: original drawing of Witold Lipiński presented at the exhibition *Shape of Dreams – The Architecture of Witold Lipiński* Museum of Architecture in Wrocław, source: author (2023)

in the shape of an igloo in Zalesie in Wrocław. Discussions about the final shape of the investment lasted until 1963, when Lipiński's design was finally chosen as more attractive and, due to the prefabricated steel structure, potentially cheaper. The architectural form comprised of three disks bound by the structural core element. The facility was located at the very top of the mountain arranged on three levels. The lowest disc was occupied by technical rooms, a restaurant and accommodation rooms, while the middle one was intended primarily for station staff. The highest disk – was to be the heart of the observatory. It had a terrace on the roof and a gallery around it. This is where the measuring equipment and the position of the meteorologist-observer were to be located.

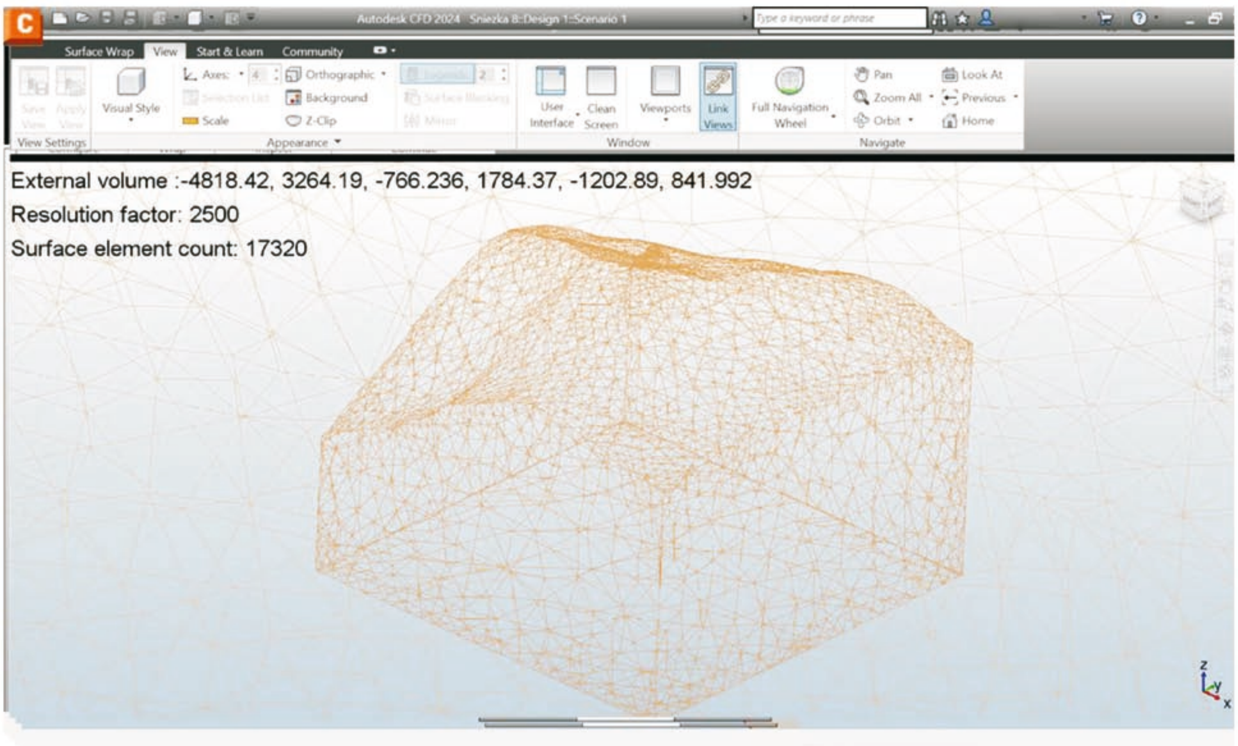
Recalling his inspirations Witold Lipiński mentioned three sources. The first was climate characterized by harsh weather conditions – the only sensible response to the hurricane winds at the top of Śnieżka was the use of aerodynamic building forms. As an amateur pilot Lipiński knew this perfectly well. As the second source, he indicated nature with rock formations shaped by erosion, so characteristic of the Karkonosze Mountains. As Witold Lipiński explained: "*I was suggested by the rock groups formed by erosion, characteristic of the Karkonosze Mountains. I borrowed the future shape of the object from the piles of elliptical boulders. There was also an aerodynamic aspect at play, dominant in the design of airplanes, which I read a lot about as a passionate glider pilot*" [Ł. Wojciechowski 2014]. Several glider study flights that Lipiński made over the peaks, helped him to come to the conclusion that the most resistant form to the prevailing conditions would be the circular form. It is impossible to predict the dominant wind direction on Śnieżka – it blows almost always and from every direction. The structure of the disks is a steel truss, centrally supported on a concrete foundation [Ł. Wojciechowski 2014]. Jerzy Ramotowski gives the opinion of prof. W. Wawrzyniak "*Śnieżka with its three disks is primarily a variation on the Karkonosze boulders polished by mountain winds over millions of years*" [J. Ramotowski 2012]. Only in third place did pop culture fascination with unidentified flying objects appear.

Construction at an altitude of 1,602 m above sea level required an individual design that would respond to difficult weather conditions, fit into the silhouette of the mountain, and at the same time fulfill a propaganda role. Lipiński managed to reconcile these apparent contradictions in his concept of three disks connected by a vertical core resting on a foundation embedded in the terrain. Wojciechowski quotes Jerzy Hryniewiecki's opinion from 1965: "*[the disks] are a form of a set of central elements influenced by the mood of the climate, strong winds and the need to create an interior that is as connected and closed as possible, and at the same time providing the widest possible panoramic possibilities. Cutting the bowl off from the terrain allowed for minimal interference in the shape of the mountain peak*" [Ł. Wojciechowski 2014].

One of the concept drawings of a longitudinal section of the building shows airflow as originally designed and drawn by Lipiński. The architectural form of the building is clearly aerodynamic, ensuring free and continuous wind flow through its parts (Fig. 9.). Both primary inspiration for architectural form (eroded rock-pile) and secondary (aerodynamic forms of glider plane) show intuitive understanding of building aerodynamics. In both aspects wind flow is an important factor. Its energy, velocity, the pressure it creates, humidity, and

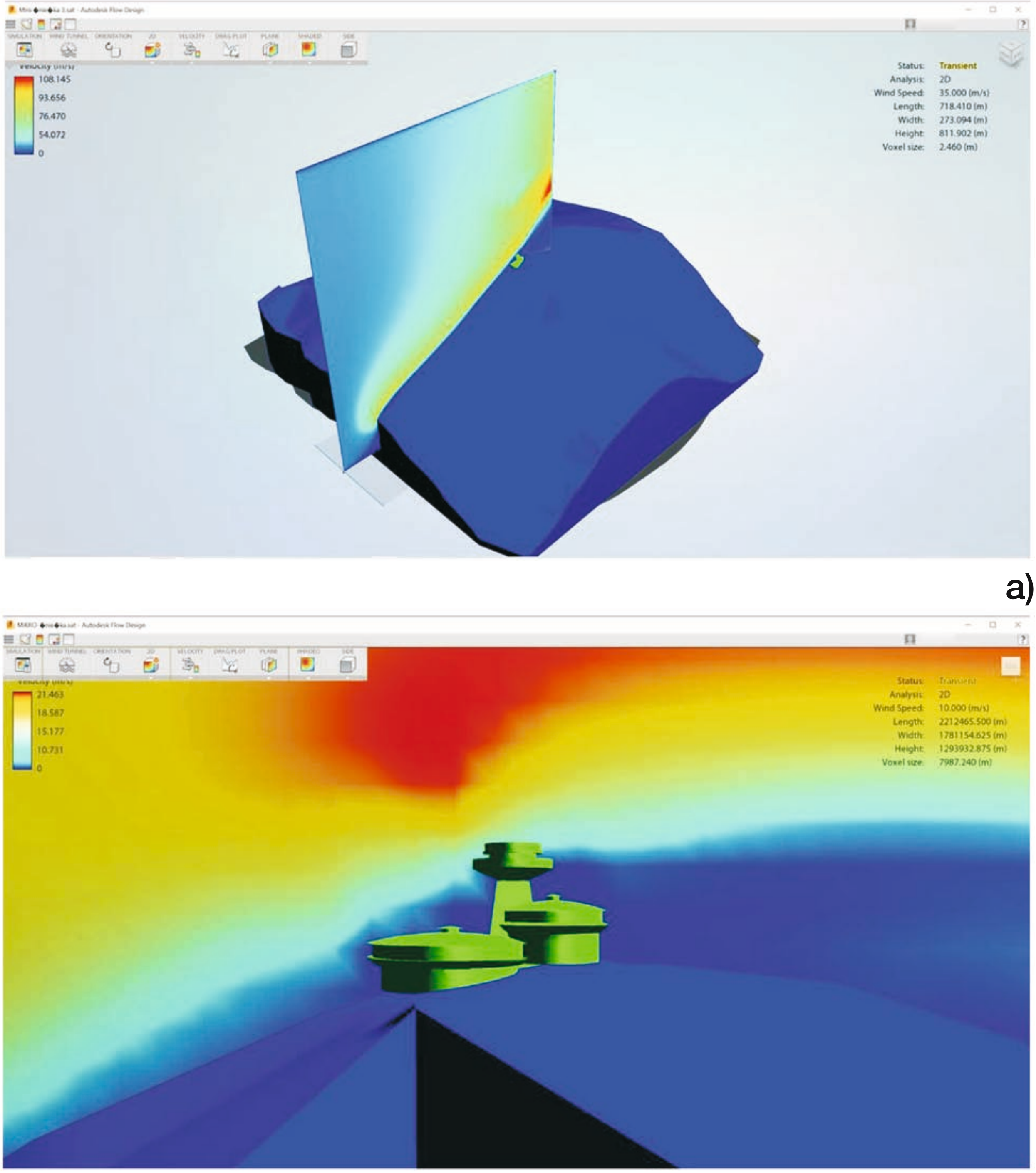


a)



b)

Fig. 10 a–b. High Mountain Meteorological Observatory on Śnieżka, a) 3D model, b) complex mesh model generated in Autodesk CFD. Source: author (2023)



b)

Fig. 11a–b. High Mountain Meteorological Observatory on Śnieżka, a–b) meshless CFD analysis in Autodesk Flow Design. Source: author (2023)

the particles it carries create continuous environmental impact on the building and in longstanding terms causes erosion of rocks. Śnieżka observatory is located on the top of the mountain and exposed to extreme weather conditions.

The observatory building is located at the height where climatic loads reach high values that determine the safety of the structure. The location of the building is considered one of the windiest places in Europe, with recorded wind speeds reaching 240 km/h. The wind was highlighted to clarify the aerodynamic idea of continuous and undisrupted flow of wind that is extreme at the peak of the mountain at an altitude of 1,602 m above sea level. According to measurements, wind speeds lower than 10 m/s are recorded only 60 days a year.

The construction of the observatory was done in the years 1966–1974. It has the form of three interconnected disc – or saucer-shaped shapes. According to Łukasz Wojciechowski, "*The Observatory of the National Hydrological and Meteorological Institute is Witold Lipiński's greatest achievement. It resembles some of the designs of Frank Lloyd Wright, John Lautner or the visions of the American set designer Norman Bel Geddes. It is the first such futuristic building in Poland incorporated into the landscape. The project was in line with the stylistic trends of the time, inspired by the conquest of space and the development of science fiction*" [Ł. Wojciechowski 2014]. In 2020, by the decision of the Provincial Conservator of Monuments of Lower Silesia, the facility was included into the register of monuments.

As Wojciechowski says: "*The middle plate contains the employees' living rooms and a kitchen with a dining room. At the top there is an observation post with a terrace, where you can conduct research in the harsh climate of Śnieżka [...] The foundations for the observatory are made of reinforced concrete - the benches rest on the rock, the core and brick walls are reinforced with reinforced concrete pins and rings, while the disks are made entirely of steel – the lattice elements were prefabricated*" [Ł. Wojciechowski 2014].

In 2009, under severe weather conditions, the lower part of the highest disk collapsed, threatening the lower structure. Fortunately, two years after the disaster, this fragment was rebuilt and the saucer's original shape was restored. The facility still functions in accordance with its original assumptions and is one of two Polish observatories of the Institute of Meteorology and Water Management operating in the global system of high-mountain stations [P. Gadomska 2020].

High Mountain Meteorological Observatory on Śnieżka wind analysis run in Autodesk CFD is based on advanced meshing of initial model (Fig. 10a–b). Since it is a professional CFD tool, solving each design study takes time providing rather obvious and not requiring high detail resolution.

The meshless CFD analysis in Autodesk Flow Design provides good interoperability between the domains of architectural design and building aerodynamics (Fig. 11a-b). Students and architecture practitioners can use this tool for rapid simulations of architectural forms created during the conceptual design process. This together with quantitative analysis of solar radiation and natural lighting fully demonstrates the link between the architecture and surrounding environment.

A key issue in architectural education is to find the right proportion between simulation accuracy and computational requirements. Simplified modelling strategies like voxel based systems, as well as dynamic visualization of flows of wind lines and wind planes significantly increase the speed of calculations needed for simulation generation.

CONCLUSIONS

Wind engineering is a combination of art and science, and it is important for structural engineers to understand just enough to check that the right studies are being conducted and, if not the reasons for unusual results, the appropriate questions to ask to elicit explanations. This model is also easier to modify if a range of building shapes are being investigated. Form-finding studies are sometimes used during concept design of particularly slender and wind sensitive towers to optimize building shape and minimize building responses. Previously, most building-related issues such as ventilation analysis, wind loading, wind environment etc. were examined using wind tunnel tests. Nowadays all these tests can be done effectively with CFD which can resolve all of the above-mentioned issues in a relatively short time period. CFD stands for Computational Fluid Dynamics and is a type of analysis that uses a numerical method to solve and analyze problems related to particle flows. Computer simulations can be used to predict the behavior of air and other fluids as they interact with objects, such as wind shear, thermals, or temperature inversions.

Architects do not require high-end CFD applications in school or in practice. Available CFD software applications are eligible to easily run air flow studies, such as the effect of wind around designed buildings. Simulation based analysis results, particularly of airflow parameters in the vicinity of buildings, can form a common general framework methodology for architectural, structural and mechanical engineering as well as for the renewable energy sources industry. Presented software tools are valuable instruments in architectural education to enrich students' profile as professional architects ready to design in close cooperation with other disciplines in integrated design processes. Research-based Design is commonly the most used work methodology in the architecture discipline. The connection between research and design gradually becomes established, the question of how to construct knowledge and understanding out of a design or a design process increases in significance. Accessible software tools and applications are valuable instruments in in-depth studies required in the conceptual phase of the architectural design process.

LITERATURE

1. **Anderson J.D. Jr. (2008)**, *Some Reflections on the History of Fluid Dynamics*, in: *The Handbook of Fluid Dynamics, ed. R.W. Johnson, CRC Press–Springer, Boca Raton–Heidelberg.*
2. **Autodesk Support (2023)**, *Flow Design vs. Autodesk CFD*, https://www.autodesk.com/support/technical/article/caas/sfdcarticles/sfdcarticles/Flow-Design-vs-Autodesk-CFD.html [access: 1.07.2024].
3. **Cholewiński M. (2021)**, *Budowa obserwatorium na Śnieżce 1973 r.*, https://fotopolska.eu/Sniezka-_1602_m_n.p.m.,552,48?f=1772421-foto [access: 1.07.2024].
4. **Designing Buildings (2022)**, *Aerodynamics*, https://www.designingbuildings.co.uk/wiki/Aerodynamics [access: 1.07.2024].
5. **Gadomska P. (2020)**, *Będzie remont Marsjańskich Spodków Śnieżki, ale kiedy?*, "Jelenia Góra Nasze Miasto", 5 marca.
6. **Geurts C.P.W**. **(2005)**, *The use of wind tunnel experiments for wind loads on structures*, TNO Built Environment and Geosciences, Delft, The Netherlands.
7. **Kaijima S., Bouffanais R., Willcox K., Naidu S. (2013)**, *Computational fluid dynamics for architectural design*, "Architectural Design", 83(2), 118–123.
8. **Kolarevic B. (2003)**, *Computing the performative in architecture*, in: *Proceedings of the 21th eCAADe Conference: Digital Design. Graz, Austria*, 17–20.
9. **Kolarevic B., Malkawi A.M. (2005)**, *Performative Architecture: Beyond Instrumentality*, Spon Press, New York–London.
10. **Kowalska M**. **(2021)**, *Remont obserwatorium na Śnieżce jeszcze w tym roku*, „Architektura & Biznes", https://www.architekturaibiznes.pl/juz-niebawem-remont-obserwatorium-na-sniezce,7524.html [access: 1.07.2024].
11. **Kyoto Protocol (1998)**, *Kyoto Protocol to the United Nations framework convention on climate change*, Kyoto.
12. **Larosea G.L., Franck N. (1997)**, *Early wind engineering experiments in Denmark*, "Journal of Wind Engineering and Industrial Aerodynamics", 72, 493–499.
13. **Laboratorium Inżynierii Wiatrowej Politechnika Krakowska (2008)**, http://www.windlab.pl/zrealizowane-prace/pulawska_warszawa/ [access: 1.07.2024].
14. **Laboratorium Inżynierii Wiatrowej Politechnika Krakowska (2013)**, http://www.windlab.pl/zrealizowane-prace/grzybowska_warszawa/ [access: 1.07.2024].
15. **Ladybug Tools LLC (2023)**, *Butterfly*, https://www.ladybug.tools/butterfly.html [access: 1.07.2024].
16. **National Academies of Sciences, Engineering, and Medicine** (2016), *Attribution of extreme weather events in the context of climate change*, National Academies Press.
17. **Nova A. (2006)**, *The role of the winds in architectural theory from Vitruvius to Scamozzi*, in: *Aeolian winds and the spirit in Renaissance architecture*, ed. B. Kenda, Academia Eolia revisited, London, 70–86.
18. **Ramotowski J.** (2012), *Profesor architekt Witold Lipiński i jego pasje*, "Studia Łomżyńskie", 23, 217–225.
19. **TOI: Design Informatics** (2020), *Flow Design – wind simulation*, TU Delft, Faculty of Architecture, http://wiki.bk.tudelft.nl/toi-pedia/Flow_Design_-_windsimulation [access: 10.12.2023].
20. **Wojciechowski Ł. (2014)**, *Pierwsze w Polsce – Kosmiczne obserwatorium*, "Architektura Murator", 3, 20–21.
21. **Yao J.W., Lin Y.Q., Zheng J.Y., Yuan P.F. (2018)**, *A "Dynamic Form-Finding". Approach to Environmental-Performance Building Design*, "International Journal of High-Rise Buildings", 7(2), 145–151.