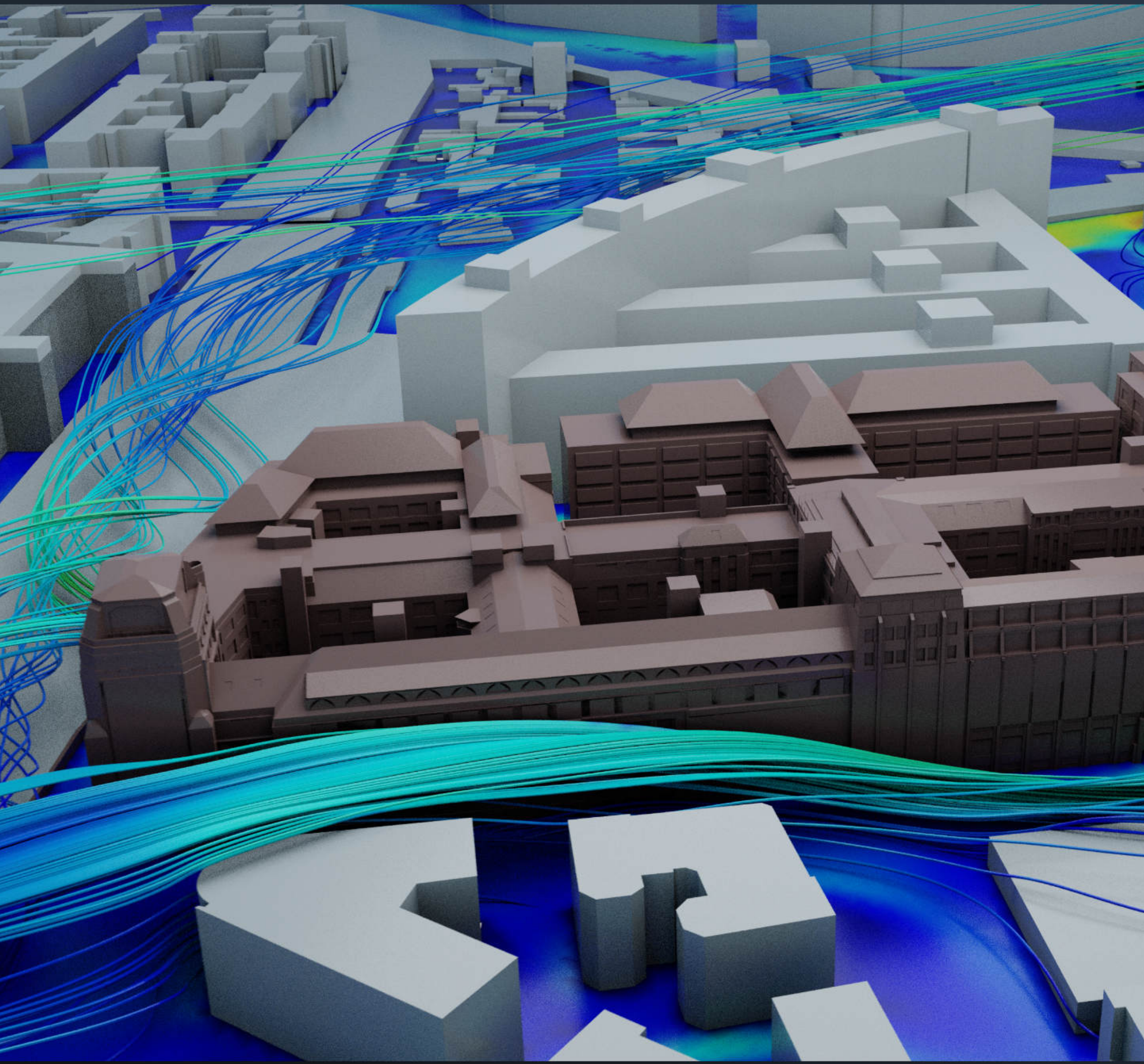

CFD Study

BERLINER BREMSENWERK

Pedestrian Wind Comfort Assessment using
Computational Fluid Dynamics for the Berliner Bremsenwerk

v1.0

Document reference

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Content

1. Executive Summary

Purpose and Scope

The purpose of this report is to perform a Computational Fluid Dynamics (CFD) analysis for the Berliner Bremsenwerk, a building located in Berlin. The analysis serves dual objectives: firstly, to evaluate Pedestrian Wind Comfort (PWC) in the surrounding area and secondly, to assess the wind loads on the structure itself. The scope encompasses CFD modeling, various simulation scenarios, and comprehensive assessments of wind impact at both structural and pedestrian levels. These evaluations are pivotal for ensuring the building's structural integrity, as well as the comfort and safety of pedestrians in its vicinity.

Study Conditions

The following table provides a view of the essential conditions and parameters that the study is based on:

Parameter	**Description**
Site location	
Address	Am Bremsenwerk 1, 10317 Berlin, Germany
Latitude	52.505772°
Longitude	13.473673°
Wind Action Standard	
Standard	EN 1991-1-4:2005+A1:2010
Wind Exposure	
Direction	0° to 360°: Urban environment
Wind Data Source	
Station	Weather station DEU_BE_Berlin-Tempelhof.AP.103840_TMYx
Distance to Site	6.44 km

Table 1.1: Parameters used in the study

Figure 1.1: Site location

Weather station

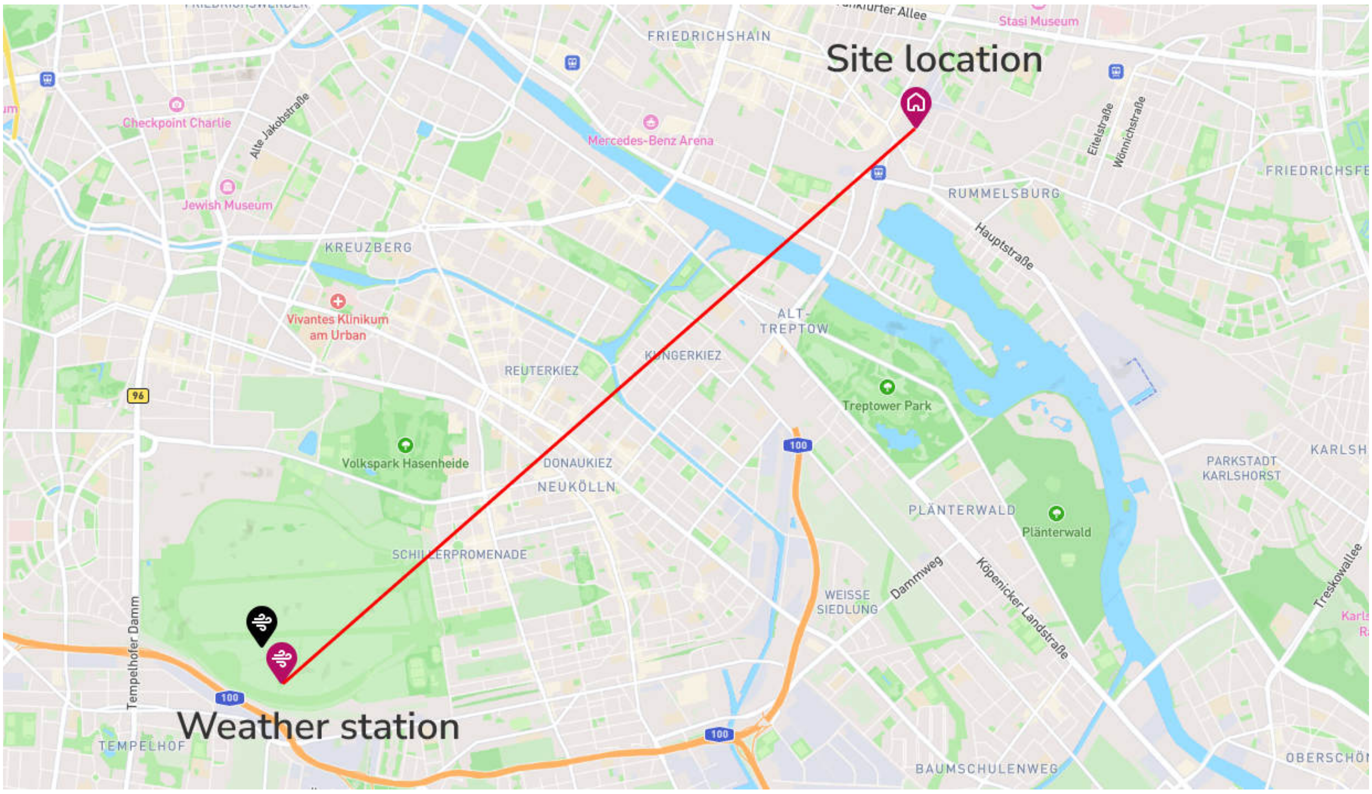

Figure 1.2: Site and weather station location (distance: 6.44 km)

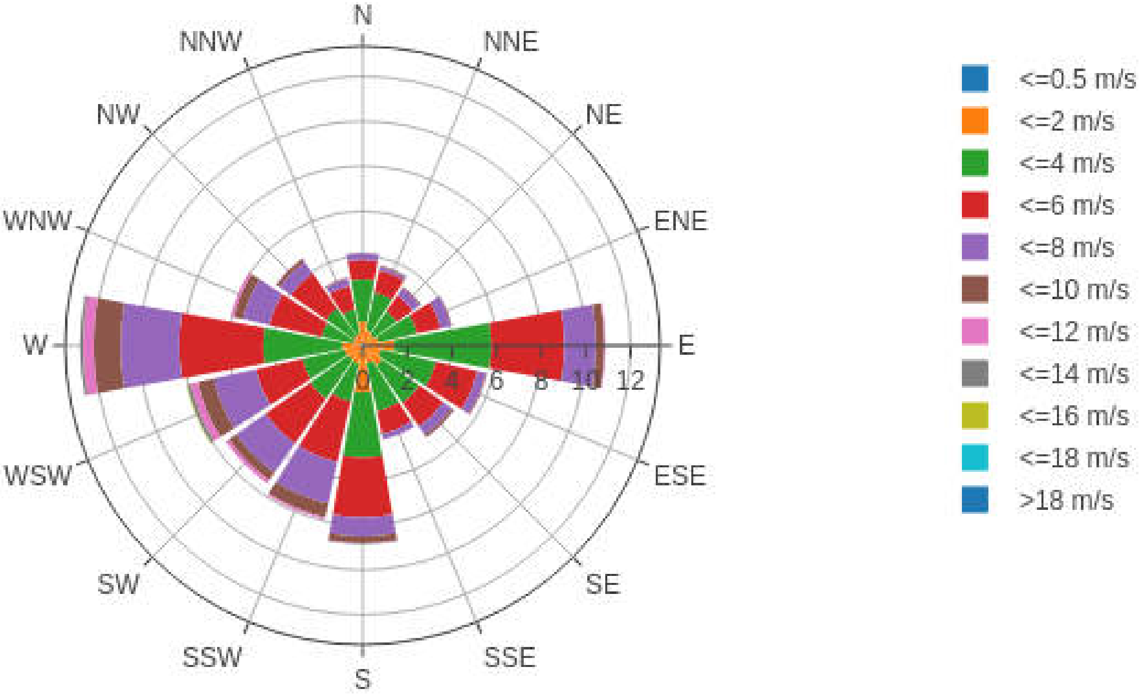

Figure 1.3: Wind rose (Weather station DEU_BE_Berlin-Tempelhof.AP.103840_TMYx)

Wind directions

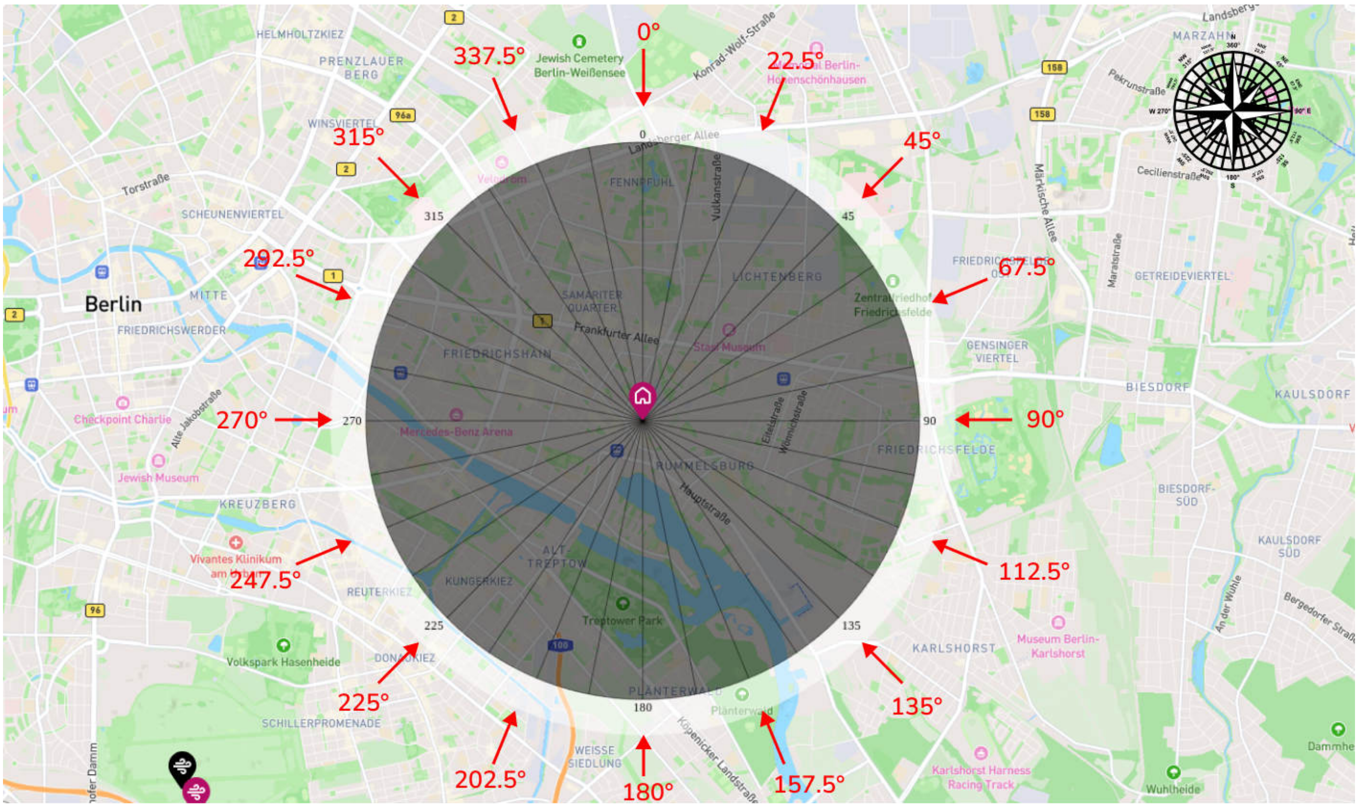

Figure 1.4: Wind directions used in the study

Direction [deg]	Frequency [%]	Velocity [m/s]
270 (W)	12.66	4.31
90 (E)	10.89	3.40
180 (S)	8.85	2.72
247.5 (WSW)	8.10	4.12
202.5 (SSW)	7.93	4.36
225 (SW)	7.48	4.00
292.5 (WNW)	6.04	4.34
112.5 (ESE)	5.72	3.17
135 (SE)	5.02	2.79
315 (NW)	4.78	3.73
157.5 (SSE)	4.3	2.79
0 (N)	4.14	2.37
67.5 (ENE)	4.10	2.99
22.5 (NNE)	3.65	2.95
45 (NE)	3.19	2.95
337.5 (NNW)	3.15	3.14

Table 1.2: 10-m wind speed and frequency of occurrence for different wind directions as measured by the weather station DEU_BE_Berlin-Tempelhof.AP.103840_TMYx

Pedestrian Wind Comfort Map

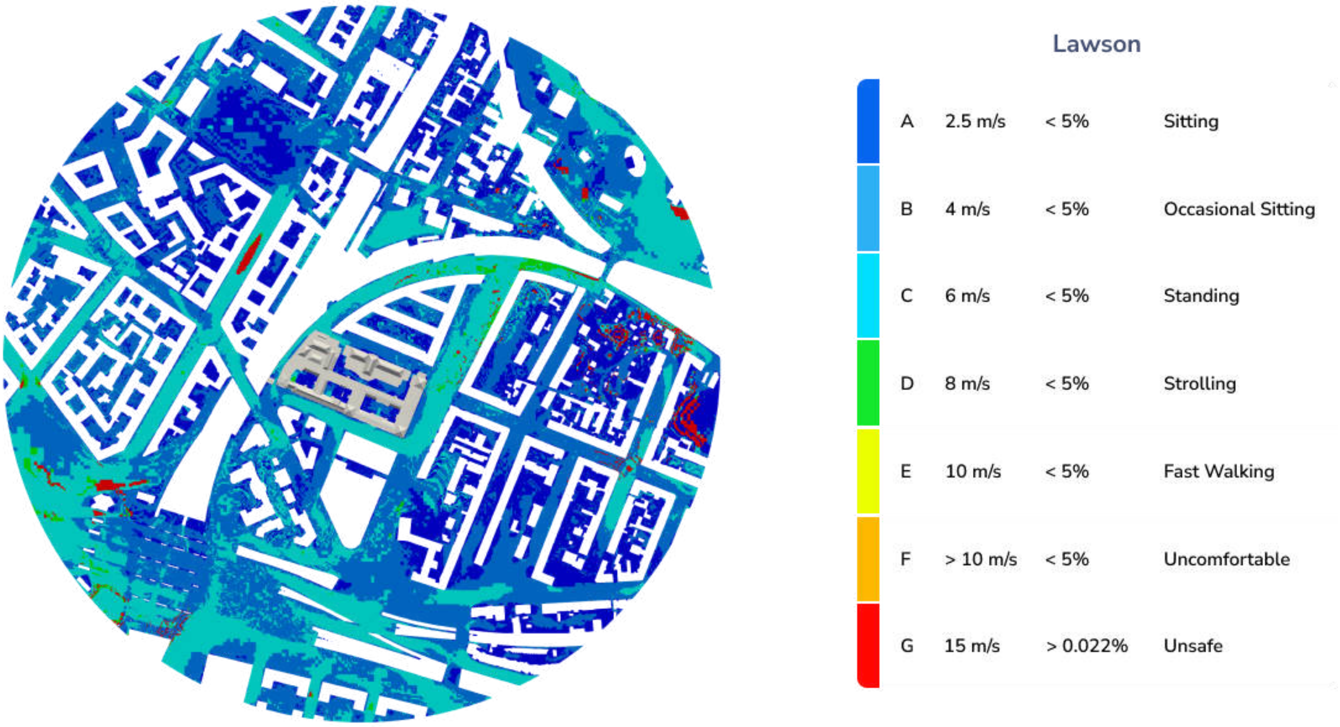

Figure 1.5: Wind comfort map - Lawson criteria

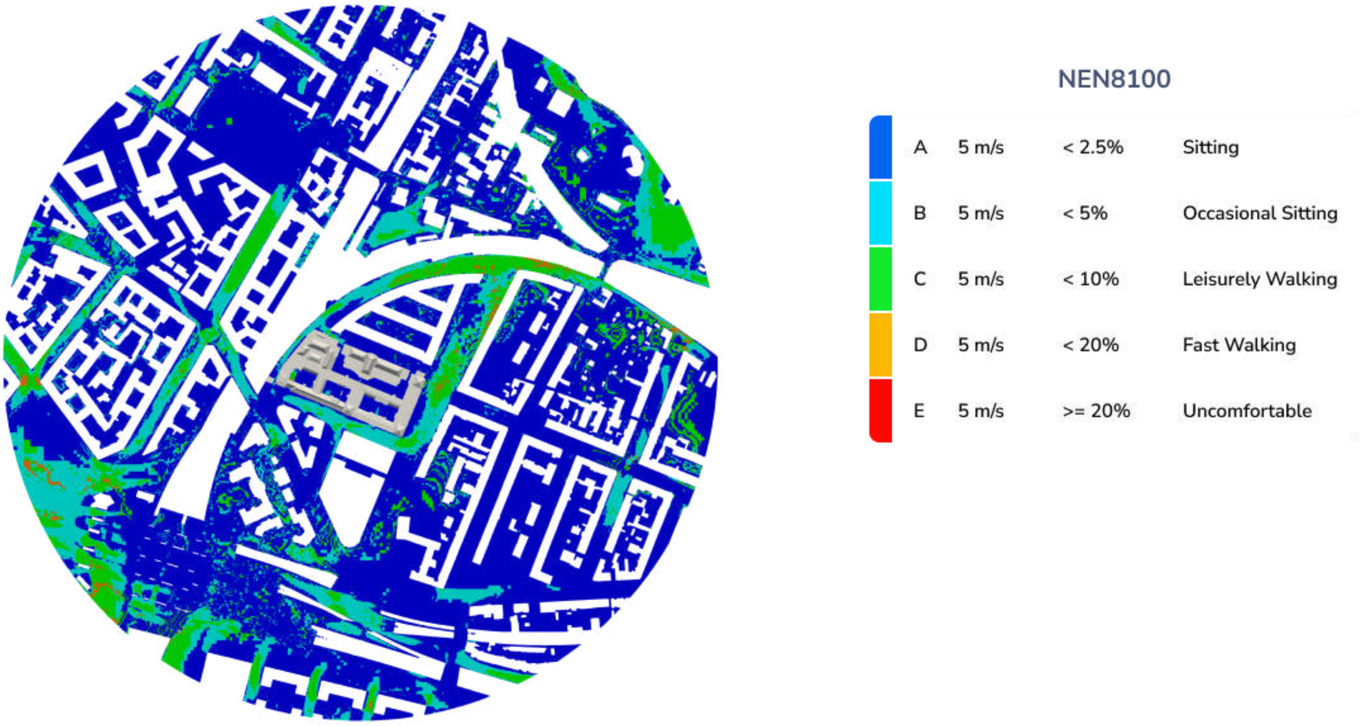

Figure 1.6: Wind comfort map - NEN8100 criteria

2. Introduction

In the modern era, the transition from costly physical tests to computer simulations has led to significant savings in both time and costs. This change is visible across a broad range of sectors like aerospace, urban planning, and manufacturing. One pivotal application of such simulation technologies, specifically Computational Fluid Dynamics (CFD), is in the area of microclimate assessment in urban environments.

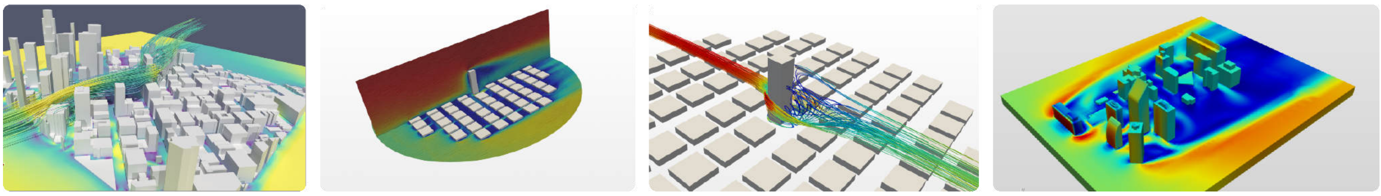

Figure 2.1: Examples for CFD studies in urban environment

Fueling this rapid transition are relentless advancements in numerical algorithms, alongside increasingly cost-effective computational power. These have expanded the scope of CFD, empowering it to address complex issues in urban wind engineering, ranging from wind loads on infrastructures like buildings and bridges to more nuanced concerns such as Pedestrian Wind Comfort (PWC). The capability of CFD to offer detailed wind flow insights at specific geographic locations, under both historical and prospective future conditions, has found applications beyond urban planning, extending into climate and environmental modeling.

Microclimate CFD analysis is a pivotal tool for both planning new structures and modifying existing ones. By employing CFD techniques, we can dissect and visualize the wind patterns around a building or a site, thereby understanding how different structural features influence airflow and comfort.

Particularly PWC is a critical aspect of a city's overall livability and is essential for the development of new buildings as well as modifications to existing structures. PWC deals with how wind, altered by urban elements like high-rise buildings, impacts people at ground level, sometimes even posing safety risks. For example, changes to structures such as the Bremsenwerk complex can significantly alter local wind conditions, making areas less comfortable or even hazardous for pedestrians. To address these concerns effectively, a thorough understanding of wind flow patterns is indispensable.

Two trends exacerbate concerns about urban wind conditions: the escalation of climate change, leading to more frequent extreme weather, and increasing urban density. In response, the European Union is implementing legislation to mitigate these challenges, underscoring the critical role of microclimate analysis in adapting urban areas for future resilience. Adding to this, cities such as London and Leeds have their own "Wind Microclimate Guidelines for Developments," a trend expected to spread across European cities, highlighting the need for thorough wind studies.

The core objective of this study is to gauge the wind conditions affecting pedestrian comfort at the newly reconfigured Bremsenwerk site in Berlin, which is now disconnected from neighboring structures. Utilizing wind comfort standards, the study aims to assess the suitability of various site sections for designated pedestrian activities, such as standing, sitting, and leisurely walking. The study is particularly focused on identifying any hazardous areas that could jeopardize pedestrian safety. By analyzing 16 distinct wind directions tailored to Berlin's unique weather conditions, the study narrows its focus on the most prevalent and impactful wind patterns affecting the site. Given the increasing uncertainties related to climate change, this investigation is crucial for future-proofing urban designs against imminent environmental changes.

3. Project description

3.1. Analysis subject: Berliner Bremsenwerk

The subject of this CFD analysis is the Bremsenwerk complex (Figure 3.1), located in a densely populated area of Berlin. This location is currently undergoing renovation led by *Signa Real Estate*, which necessitates an updated understanding of wind patterns. The study aims to understand how two main structural elements affect the wind flow patterns around the building. The first is an elevated railroad near the building's facade, expected to significantly impact the microclimate. The second is a recent architectural change: the disconnection from a neighboring structure, which also likely influences wind dynamics. Both changes underline the necessity of a comprehensive CFD study.

All necessary 3D geometric and environmental data for the analysis have been supplied by *BIG (Bjarke Ingels Group)*. The study aims to inform the ongoing renovation and prepare the structure for future challenges related to urban density and climate change.

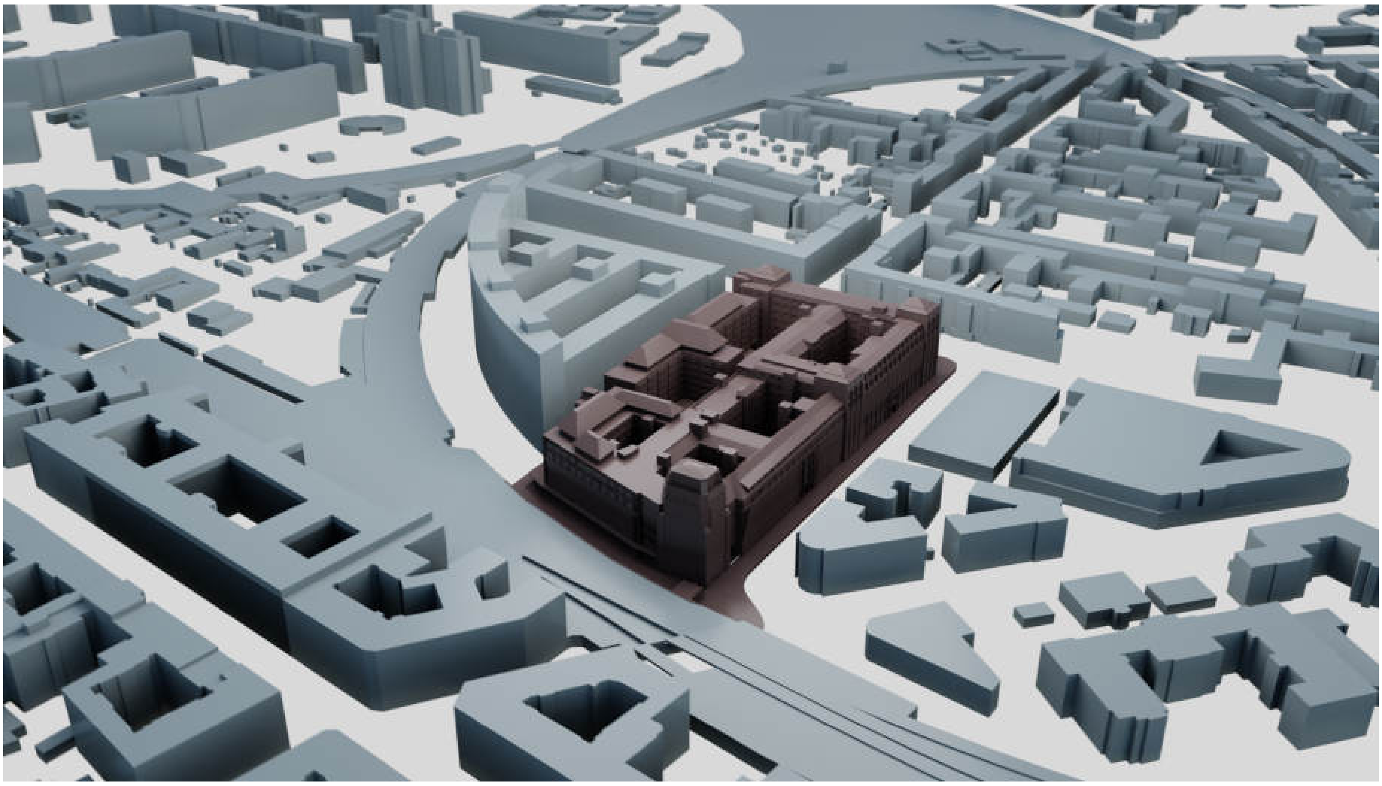

Figure 3.1: The Bremsenwerk complex in Berlin with nearby structures

3.2. Objective and scope of the study

The primary goal is to assess pedestrian comfort in the altered geometry around the Bremsenwerk complex, especially given the building's recent disconnection (Figure 3.2) from a neighboring structure. The study also aims to understand how the local microclimate could evolve due to climate change. Wind comfort standards will be applied to evaluate the site for various pedestrian activities such as sitting, walking, and standing. The study employs a Computational Fluid Dynamics (CFD) approach, utilizing Reynolds-averaged Navier-Stokes (RANS) equations for steady-state wind analysis. Sixteen different wind scenarios and directions have been considered for comprehensive analysis. Outcomes will identify regions that may be distressing or hazardous to pedestrians and propose possible solutions.

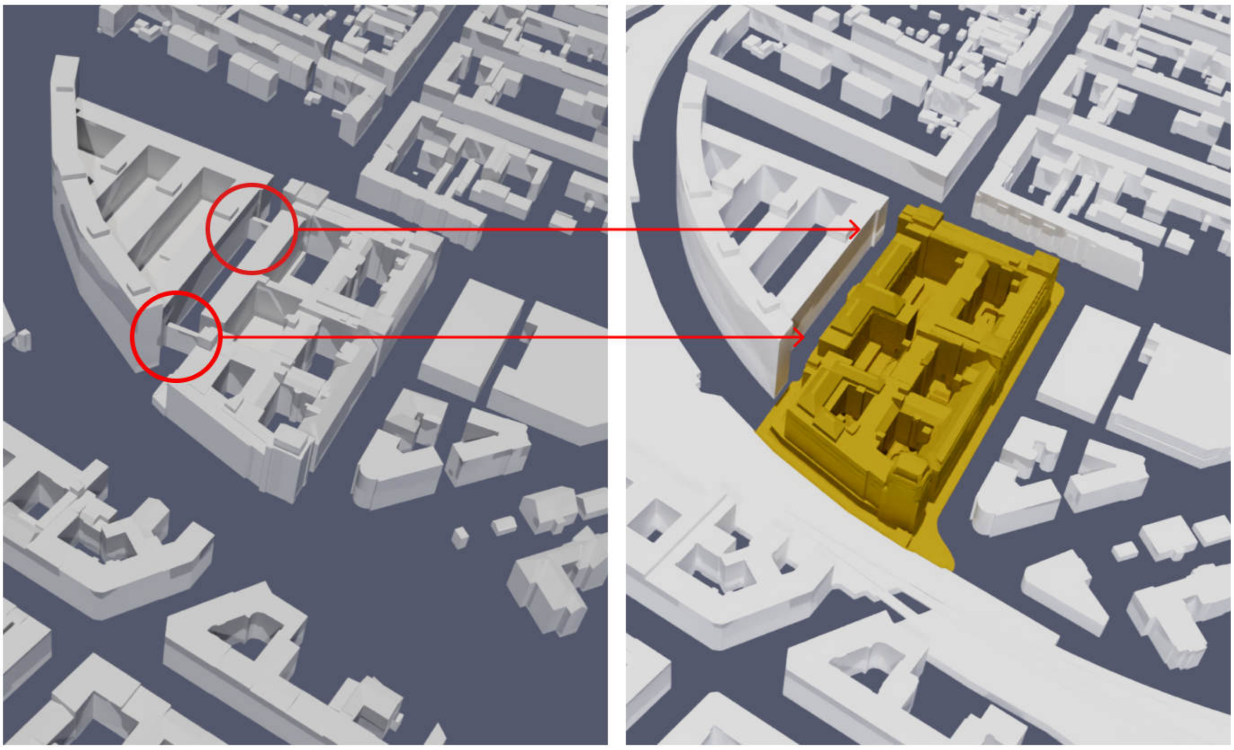

Figure 3.2: Significant design change. Left: old configuration of the building, Right: new configuration after disconnection from neighboring structure

In direct alignment with the EU Taxonomy[1] for sustainable activities, this study embodies key environmental objectives, including climate change adaptation and the sustainable use and protection of urban areas. The EU Taxonomy outlines six environmental objectives: climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, and protection and restoration of biodiversity and ecosystems. PWC inherently deals with adaptation to climate conditions, making it a pivotal aspect of sustainable urban planning. As the taxonomy requires that an activity does 'no significant harm' (DNSH) to any of the outlined environmental objectives, the emphasis on pedestrian comfort and safety in this study ensures compliance. Additionally,

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[1] EU-Taxonomy: A classification system that defines what constitutes an environmentally sustainable economic activity within the European Union. It aims to direct investments towards more sustainable technologies and businesses, providing specific criteria for activities to be deemed sustainable. (https://eu-taxonomy.info/info/eu-taxonomy-overview)

results aim to inform adaptive strategies that are in line with taxonomy criteria, thereby contributing to long-term sustainable and resilient urban infrastructure.

3.3. Building Geometry

The provided building geometry for the Bremsenwerk complex (Figure 3.3) has dimensions of 170m in width, 260m in length, and 50m in height. The model is highly detailed, incorporating an elevated wall facing the nearby elevated railroad. In areas with structures of significant scale, such as the Bremsenwerk complex, localized wind conditions can vary widely. Lower wind speeds may be observed on the leeward side, while the windward side and building edges may experience increased flow velocities due to aerodynamic effects like channeling. Such specific flow conditions can lead to decreased wind comfort or even safety hazards.

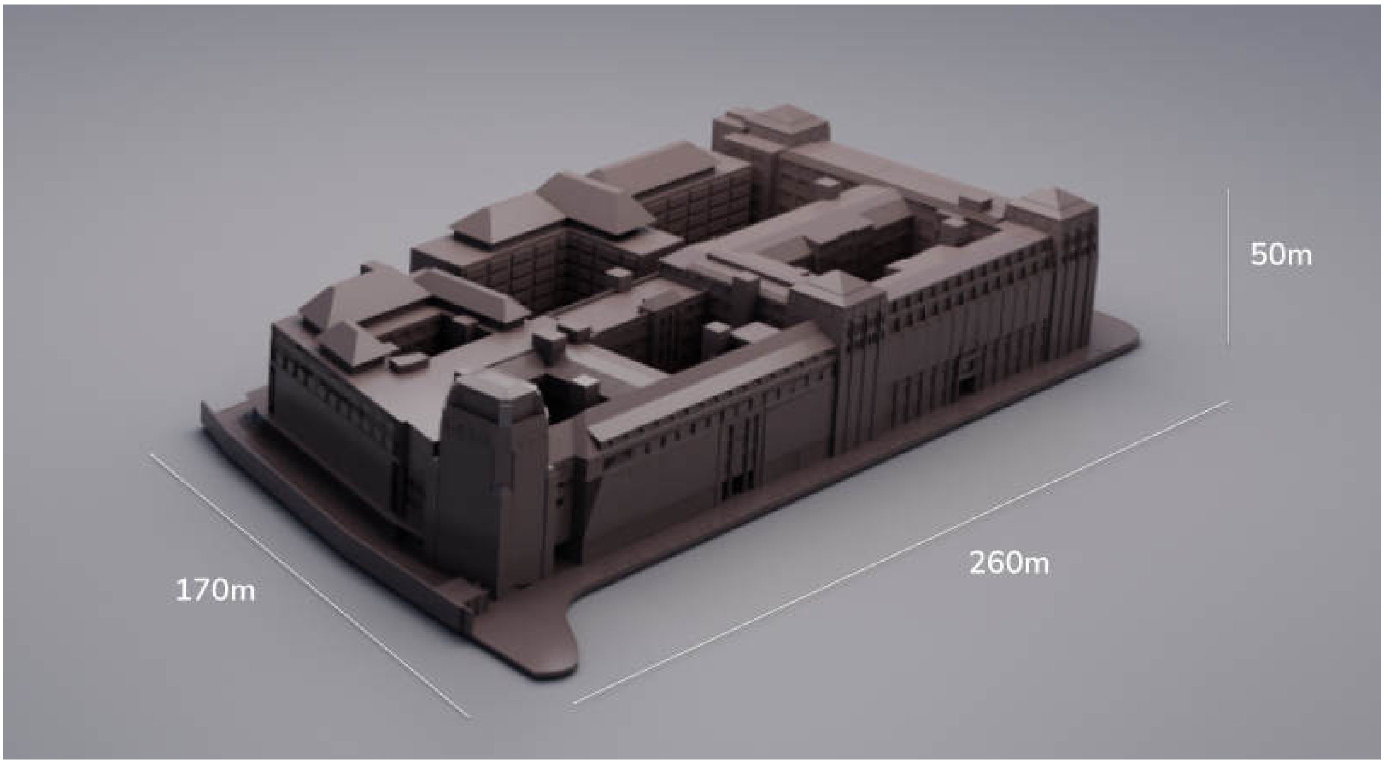


Figure 3.3: The Bremsenwerk complex with dimensions 170m x 260m x 50m

With the building's recent disconnection from its neighboring structure, the local wind dynamics are expected to change. Additionally, there are obstructions and entry points into the building's courtyard area that could also influence local wind patterns. This makes it imperative to perform a detailed wind comfort study to understand and adapt to these new conditions, thereby ensuring that areas around the complex remain comfortable and safe for pedestrians.

3.4. Site Description

The Bremsenwerk complex is situated in a densely populated area, significantly influenced by surrounding structures. Given the building's moderate height of approximately 50m, it is highly susceptible to aerodynamic interactions with neighboring buildings of similar or greater height.

The prevailing wind direction, detailed in the next chapter, predominantly comes from the West. The environment extends 750m to the West from the building. A crucial element in shaping the site's wind behavior to the North is the elevated railroad. To the East, the environment extends to about 2200m, with multiple structures contributing to the site's wind dynamics. The extension of the environment from the Bremsenwerk complex to the North and South is approximately 1500m. These dimensions provide the spatial context within which the CFD analysis will be performed, offering a comprehensive understanding of how wind flows are affected by distant structures as well as those immediately adjacent to the site.

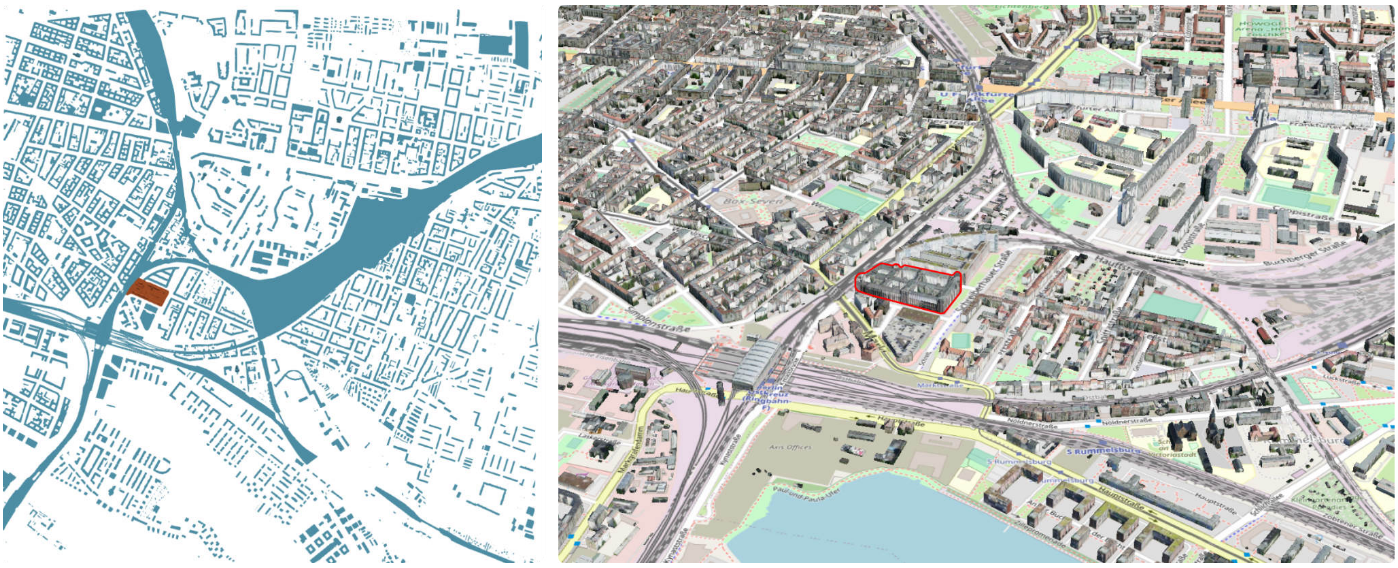


Figure 3.4: Left: Top-down view of study area. Right: 3D view showing building density

3.5. Meteorological Data

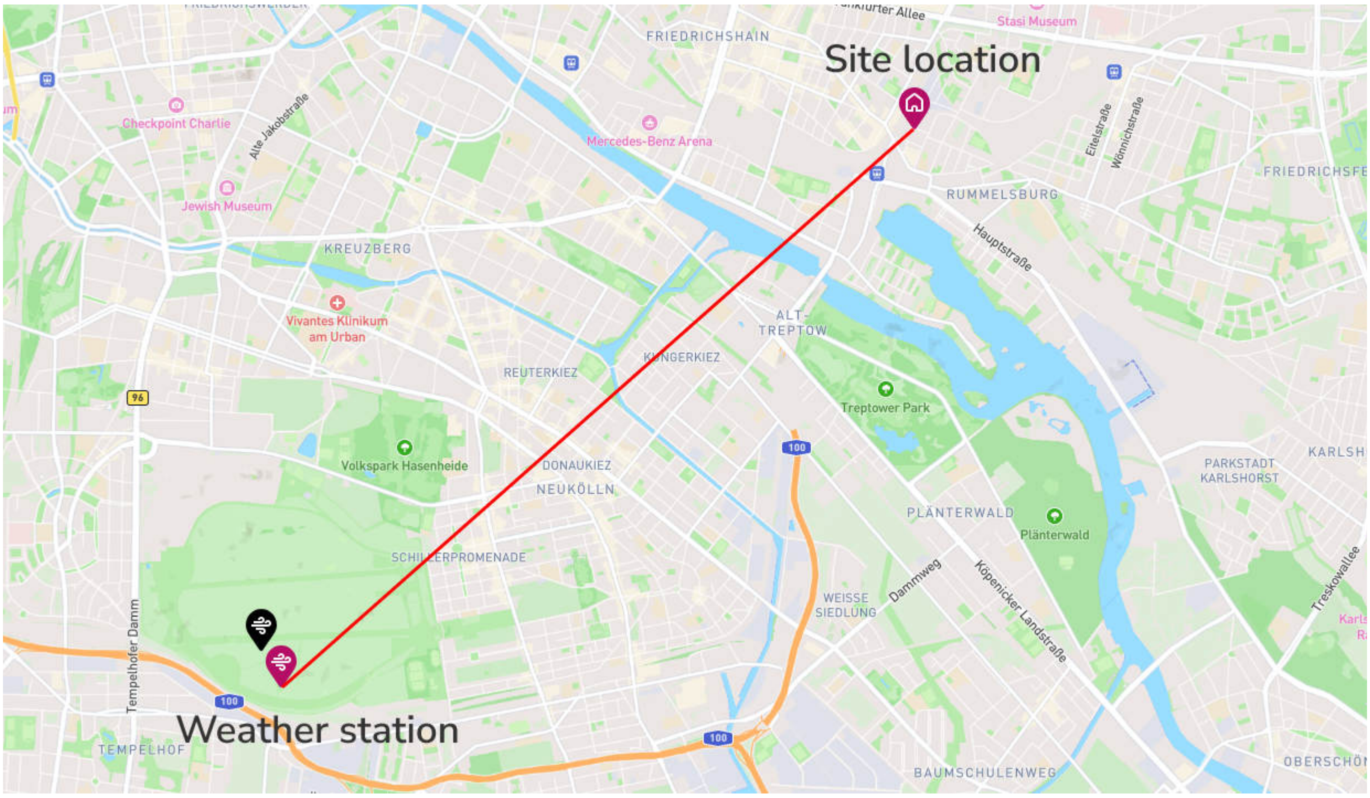


Figure 3.5: Site and weather station location (distance: 6.44 km)

The Berlin-Tempelhof weather station was selected for this study due to its proximity to the building complex and its extensive historical wind data. The station's long-term data set from 1938-2007 provides a robust foundation for understanding prevailing wind patterns, crucial for accurate CFD simulations. The wind rose for this weather station can be seen in Figure 3.6.

Figure 3.6 illustrates the long-term distribution of wind direction and speed at Berlin-Tempelhof Station, taken at a height of 10m above ground level. The data set, spanning from 1938 to 2007, reveals a clear predominance of wind coming from the western to southwestern directions. A secondary peak in wind direction is observed from the east. Winds from northern directions are comparatively rare. The most impactful wind velocities are especially frequent from the west and east. The long-term average wind speed is measured at 4.05 m/s at a height of 10m.

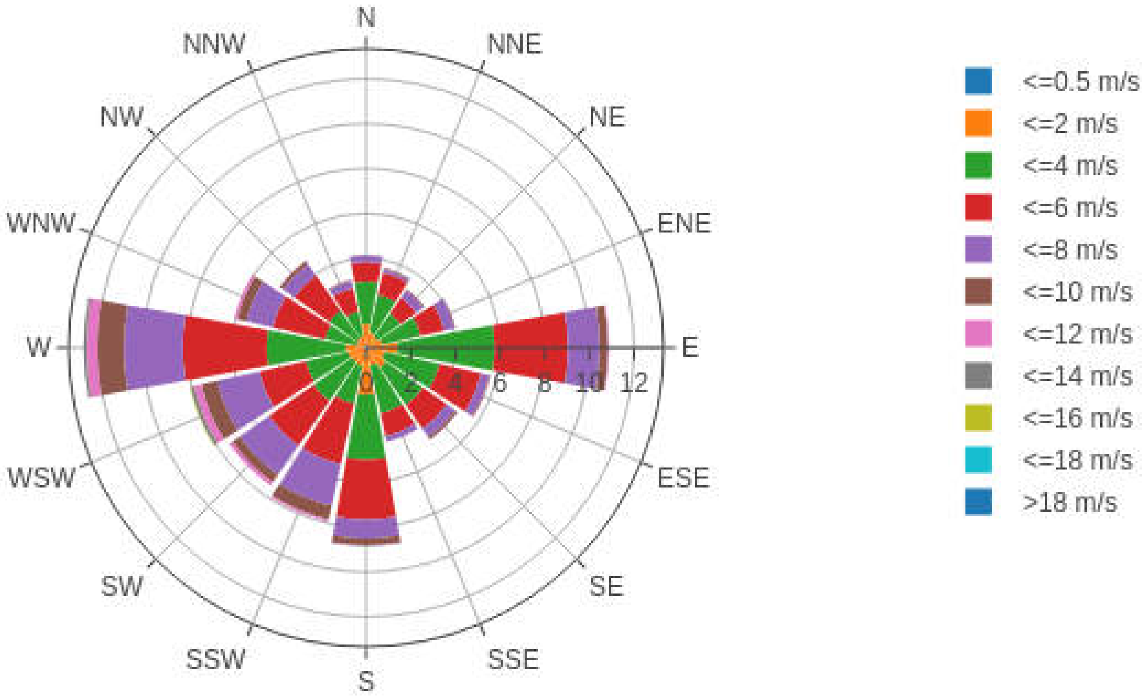


Figure 3.6: Wind rose for years 1938 - 2007
(Weather station at Berlin Tempelhof - DEU_BE_Berlin-Tempelhof.AP.103840_TMYx)

Table 3.1 provides the frequency and velocity of wind from 16 distinct directions around the Bremsenwerk complex. These directions and their respective velocities will serve as the input conditions at the inlet of the virtual wind tunnel for the CFD simulations. The most prevalent wind direction is from the West (270°) with a frequency of 12.66% and a velocity of 4.31 m/s. Eastern winds (90°) follow with a 10.89% frequency but lower velocity of 3.40 m/s. Winds from the West-Sout-West and South-West directions also show higher velocities, generally exceeding 4 m/s. Conversely, winds from the North and North-East directions are least frequent and have lower velocities. Given the variability in both wind direction and velocity, the 16 selected directions will serve as crucial input parameters for the CFD simulations, enabling a comprehensive understanding of wind comfort around the complex.

	Direction [deg]	Frequency [%]	Velocity [m/s]
1	270 (W)	12.66	4.31
2	90 (E)	10.89	3.40
3	180 (S)	8.85	2.72
4	247.5 (WSW)	8.10	4.12
5	202.5 (SSW)	7.93	4.36
6	225 (SW)	7.48	4.00
7	292.5 (WNW)	6.04	4.34
8	112.5 (ESE)	5.72	3.17
9	135 (SE)	5.02	2.79
10	315 (NW)	4.78	3.73
11	157.5 (SSE)	4.3	2.79
12	0 (N)	4.14	2.37
13	67.5 (ENE)	4.10	2.99
14	22.5 (NNE)	3.65	2.95
15	45 (NE)	3.19	2.95
16	337.5 (NNW)	3.15	3.14

Table 3.1: 16 10-m wind speed and frequency of occurrence for different wind directions as measured by the weather station DEU_BE_Berlin-Tempelhof.AP.103840_TMYx

3.6. Regulatory Framework

In the absence of a dedicated regulatory framework for wind microclimate studies in Berlin, this study will employ ***"EN 1991-1-4: Eurocode 1: Actions on Structures"*** as the governing standard.

The EN 1991-1-4: Eurocode 1: Actions on Structures standard is a European standard that outlines guidelines for calculating wind loads on building structures. It serves as a critical foundation for computational fluid dynamics (CFD) studies, like the one conducted here, which aim to simulate the wind environment around built forms. Within the context of this study, the Eurocode standard provides the necessary criteria to estimate acceptable wind pressures, flow velocities, and directions, enabling a robust, scientifically-backed assessment of wind impacts on the building and its immediate environment.

Additionally, the City of London's recommended approach for wind microclimate studies serves as a relevant reference due to the structural similarities between Berlin and London. The City of London's guidelines suggest different methodologies for wind studies based on building height relative to surrounding structures (Table 3.2).

Given that the building in this study stands at approximately 50m, aligning with the City of London's 25m to 50m category, it's appropriate to conduct either CFD simulations or wind tunnel tests to assess wind comfort.

Building Height	Recommended Approach to Wind Microclimate Studies
Similar or lower than the average height of surrounding buildings **Up to 25m**	Wind studies are not required, unless sensitive pedestrian activities are intended (e.g. around hospitals, transport hubs, etc.) or the project is located on an exposed location (e.g. edge of Thames, near a tall building)
Up to double the average height of surrounding buildings **25m to 50m**	Computational (CFD) Simulations OR Wind Tunnel Testing
Up to 4 times the average height of surrounding buildings **50m to 100m**	Computational (CFD) Simulations AND Wind Tunnel Testing
High-Rise **Above 100m**	Early Stage Massing Optimization: Wind Tunnel Testing OR Computational (CFD) Simulations Detailed Design: Wind Tunnel Testing AND Computational (CFD) Simulations to demonstrate the performance of the final building design

Table 3.2: Recommended Approach to Wind Microclimate Studies from the City of London Microclimate Guidelines from August 2019

3.7. Terrain roughness

Terrain roughness fundamentally dictates the wind velocity profile close to the ground, impacting both wind speed and direction. It is a measure that encapsulates the features of the surface over which wind travels, such as vegetation, buildings, and obstacles. The higher the roughness, the more wind speed near the ground decreases, while smoother terrains allow for less frictional drag and higher speeds. For a detailed understanding of how terrain roughness affects wind velocity profiles, refer to the figure below (Figure 3.7). This factor is crucial for accurate Computational Fluid Dynamics (CFD) simulations and subsequent wind comfort studies.

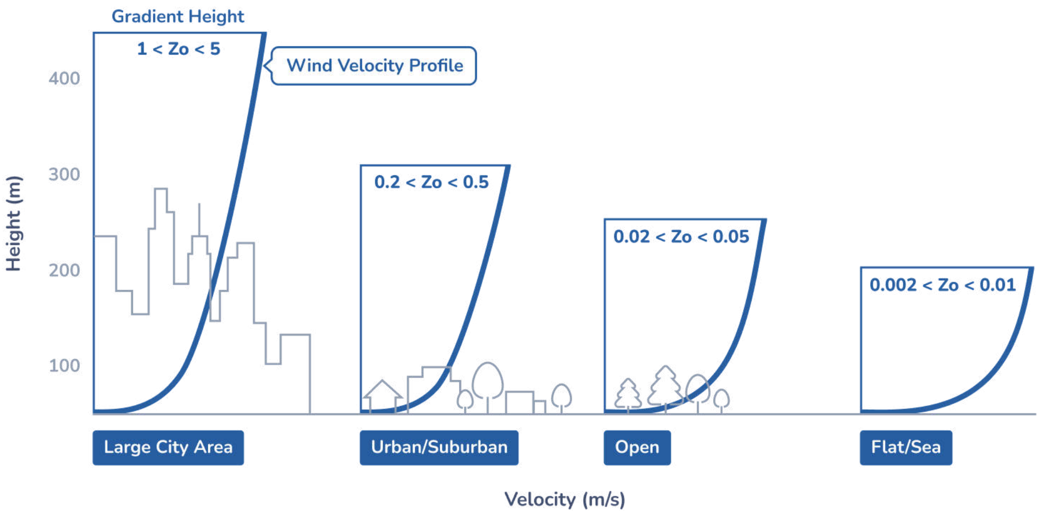


Figure 3.7: Illustration of different terrain categories and their impact on the wind velocity profile

In compliance with Eurocode EN 1991-1-4, the table 3.3 categorizes terrain into five types, from open sea to densely urbanized settings, each having corresponding roughness lengths (z_0). These categories serve as critical input parameters for Computational Fluid Dynamics (CFD) studies, as they significantly influence wind flow patterns and thereby the simulation's accuracy.

	Terrain category [m]	**Roughness length [m]**
0	Sea or coastal area exposed to the open sea	0.003
I	Lakes or flat and horizontal area with negligible vegetation and without obstacles	0.01
II	Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0.05
III	Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0.3
IV	Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1.0

Table 3.3: Terrain categories and terrain parameters

In alignment with Eurocode's terrain categories, Table 3.2 specifies the roughness categories and corresponding lengths for 16 distinct wind directions around the "Bremsenwerk" complex. Every direction is classified as “urban” terrain, substantiated by a standardized roughness length of 1.00 m. This uniform metric is attributable to the consistent building heights in the area, allowing for a single roughness length to be applied universally. The simplicity introduced by this uniformity benefits the CFD simulation by streamlining input variables without sacrificing accuracy in modeling terrain influences on wind conditions. These standard roughness parameters are crucial inputs for the CFD simulation, acting as determinants for local wind flow characteristics and thereby ensuring the precision of the wind comfort study.

Direction [deg]	**Terrain category [m]**	**Roughness length [m]**
270 (W)	Urban	1.00
90 (E)	Urban	1.00
180 (S)	Urban	1.00
247.5 (WSW)	Urban	1.00
202.5 (SSW)	Urban	1.00
225 (SW)	Urban	1.00
292.5 (WNW)	Urban	1.00
112.5 (ESE)	Urban	1.00
135 (SE)	Urban	1.00
315 (NW)	Urban	1.00
157.5 (SSE)	Urban	1.00
0 (N)	Urban	1.00
67.5 (ENE)	Urban	1.00
22.5 (NNE)	Urban	1.00
45 (NE)	Urban	1.00
337.5 (NNW)	Urban	1.00

Table 3.4: Roughness categories and corresponding lengths for varying wind directions, specifying terrain characteristics that influence wind flow

4. Methodology

4.1. Overview of CFD

Computational Fluid Dynamics (CFD) serves as a cornerstone for evaluating wind behavior and pedestrian comfort, particularly due to its cost-efficiency and high degree of accuracy. It is a numerical technique used for simulating fluid flows, including air, to assess various conditions like pedestrian wind comfort.

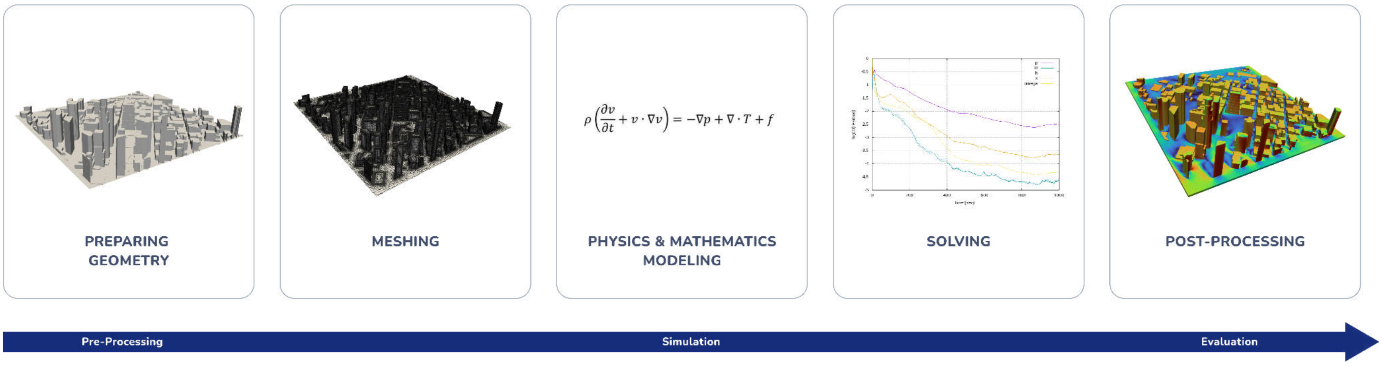


Figure 4.1: CFD workflow from Pre-Processing to Evaluation

The CFD workflow (Figure 4.1) comprises five steps:

1. **Preparing Geometry / Pre-Processing:** This initial stage involves creating a geometric model of the environment to be studied. The model can be as simple or complex as required, depending on the questions being asked and the data being sought.

2. **Meshing:** The geometric model is then divided into a grid or mesh. Each cell within the mesh represents a discrete region where the flow variables will be calculated. The quality and refinement of the mesh are directly related to the accuracy of the simulation.

3. **Physics & Mathematics Modeling:** At this stage, the governing equations for fluid dynamics, such as Navier-Stokes equations, are applied. Additional models may also be introduced to simulate turbulence, heat transfer, or other relevant phenomena.

4. **Solving Numerical Equations:** The governing equations are solved iteratively for each cell in the mesh. This is usually the most computationally intensive step, requiring powerful hardware or cluster computing.

5. **Evaluation:** Once the numerical equations are solved, the data is assessed to derive useful metrics for wind comfort. This includes examining various flow parameters like velocity, pressure, and temperature to interpret how they impact pedestrian comfort levels.

By following these steps, CFD provides a comprehensive approach to understanding how changes in the Bremsenwerk complex or any other architectural feature affect wind behavior and, consequently, pedestrian comfort.

4.2. Model Selection

For this study, the Reynolds-Averaged Navier-Stokes (RANS) equations have been selected as the governing model. RANS is a class of modeling approaches that simplifies the Navier-Stokes equations by time-averaging the equations of fluid motion. This provides a balance between computational cost and the level of detail in the results, making it a practical choice for large-scale simulations like the one conducted for the Bremsenwerk complex in Berlin.

One of the major advantages of using RANS is its efficacy in steady-state simulations, which is the case for this study. Steady-state simulations assume that flow properties at any given point do not change over time. This is a reasonable approximation for studying pedestrian wind comfort, as we are primarily interested in long-term, averaged conditions rather than transient or fluctuating wind events.

The steady-state RANS approach offers a computationally efficient yet sufficiently accurate method for capturing the wind flow patterns around the building and identifying areas of concern, such as zones where wind speed accelerates at elevated levels. Thus, the selection of the RANS model is well-justified for the goals and constraints of this particular study.

4.3. Geometric Modelling

Figure 4.2: Geometry used in the study

The geometry for the main building and its surrounding environment (Figure 3.4) was provided in a highly detailed format. However, it was not watertight, a condition where all faces and edges of the geometry are sealed with no gaps or holes. Watertight geometry is essential for CFD studies, as it ensures accurate simulations and prevents numerical errors during fluid flow computations. To make the geometry suitable for the CFD study, it was prepared to become watertight (Figure 4.3).

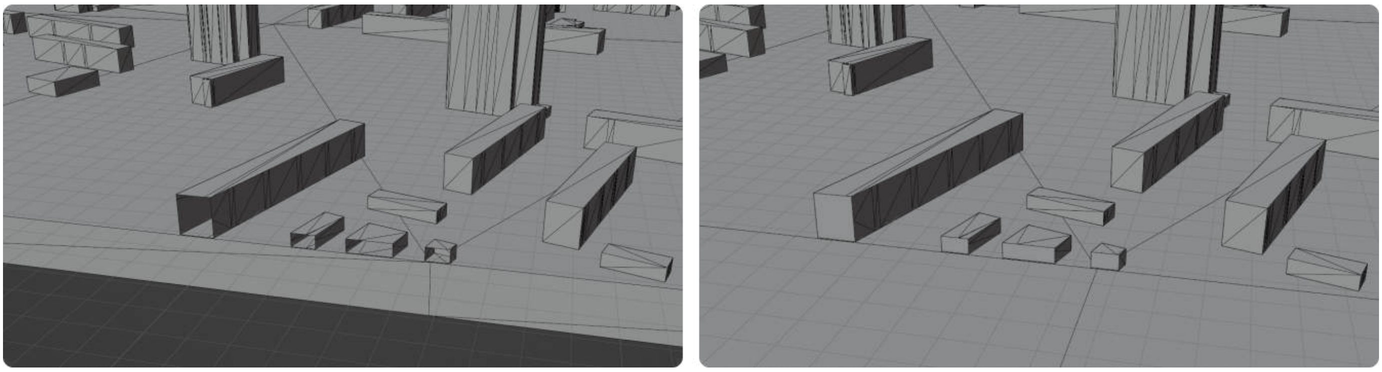


Figure 4.3: Comparison of building geometries before and after watertight modifications. Left: Original geometries with open sides. Right: Modified geometries, now watertight, ensuring more accurate CFD simulations

Additionally, the model was defeatured, meaning that unnecessary complexities like small fillets, holes, and protrusions were removed. Defeaturing is vital because it simplifies the geometry, reducing computational overhead. This is critical to avoid unnecessarily complex and time-consuming CFD calculations, thereby optimizing both computational costs and time. With these adjustments, the CFD study could focus solely on the most impactful elements for wind comfort and safety.

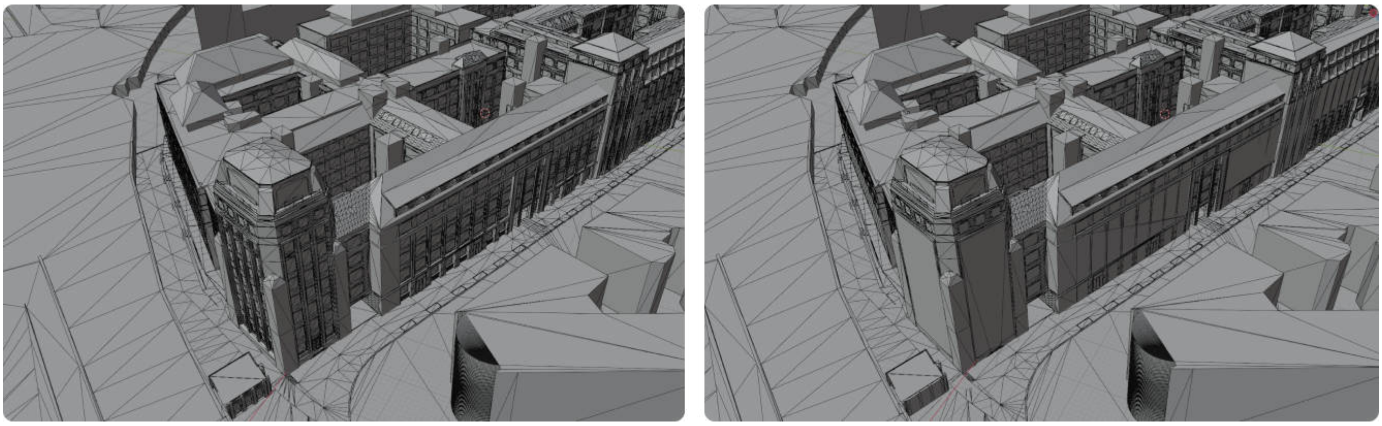


Figure 4.5: Geometry Simplification for CFD Analysis. Left: Original, highly detailed building geometry including open windows and intricate facades. Right: Streamlined geometry with most windows closed and minor details removed to reduce computational expense and time

4.4. Computational Domain

In adherence to best practice guidelines as proposed by and the AIJ [1], Franke et al. [3] and Tominaga et al. [4], several key considerations should be factored into the computational domain setup for accurate and reliable results:

- The domain ought to be box-shaped, although cylindrical domains as suggested by Kastner and Dogan [5] can yield results of comparable accuracy and convergence.
- The top boundary should be positioned at a distance of $5 \cdot H_{max}$, where H_{max} signifies the height of the tallest building within the urban environment under study.
- The outflow boundary should be situated $15 \cdot H_{max}$ away from the buildings.
- The lateral width is determined based on the blockage ratio, which should remain below 3% for CFD simulations of wind flow surrounding buildings. The blockage ratio is calculated as the ratio of the

building's frontal area (typically the area exposed to the wind) to the cross-sectional area of the wind tunnel or total inlet area in the wind's direction.

These guidelines serve as a structured approach to achieving a well-configured and scientifically rigorous computational domain. Aligned with these guidelines, three primary computational domain configurations (Figure 4.6) are considered in this study:

	Standard Box	**Rotating Box**	**Cylindrical Domain**
Advantages	Straightforward setup	Highest level of accuracy	Efficient grid, balanced accuracy, and versatility in simulating various wind directions
Limitations	Computationally demanding due to large grid; challenges in corner regions for certain wind directions	Requires individual recalculations for each new wind direction, increasing computational load	Increasing wake size inflates overall dimensions, raising computational costs

The cylindrical domain strikes a balance, providing a more efficient grid while maintaining acceptable accuracy; its geometric design further enhances its versatility, allowing for effective simulation of winds from various directions.

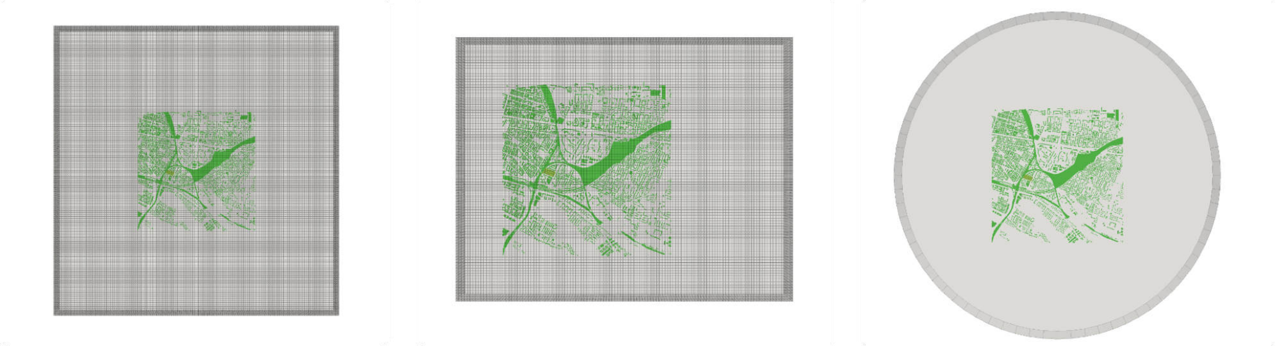
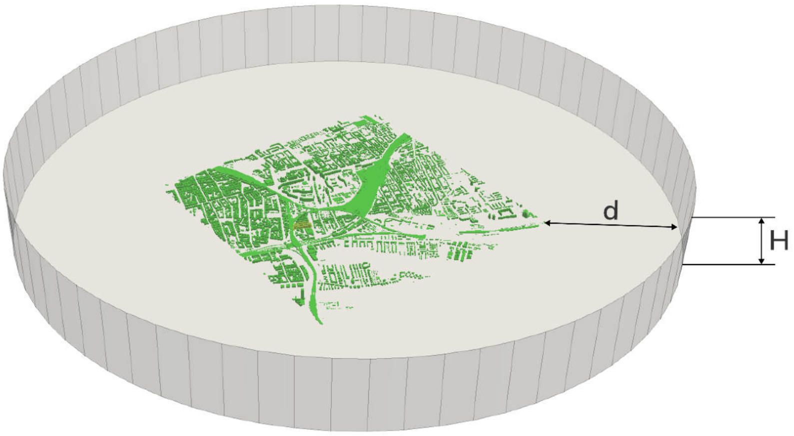


Figure 4.6: CFD Domains: Standard Box, Rotating Box, Cylindrical

In the Bremsenwerk case, the cylindrical domain (Figure 4.7) emerged as the optimal choice, not only for its capability to efficiently manage simulations across 16 different wind directions but also because it allows for the use of a single mesh for all simulations. This uniformity further streamlines the computational workflow and simplifies the task of testing each computational grid for accuracy and errors.



$H = 6 \times H_{max}$

$d = 15 \times H_{max}$

Figure 4.7: Selected cylindrical computational domain with H_{max} as the height of the highest building

4.5. Computational Grid

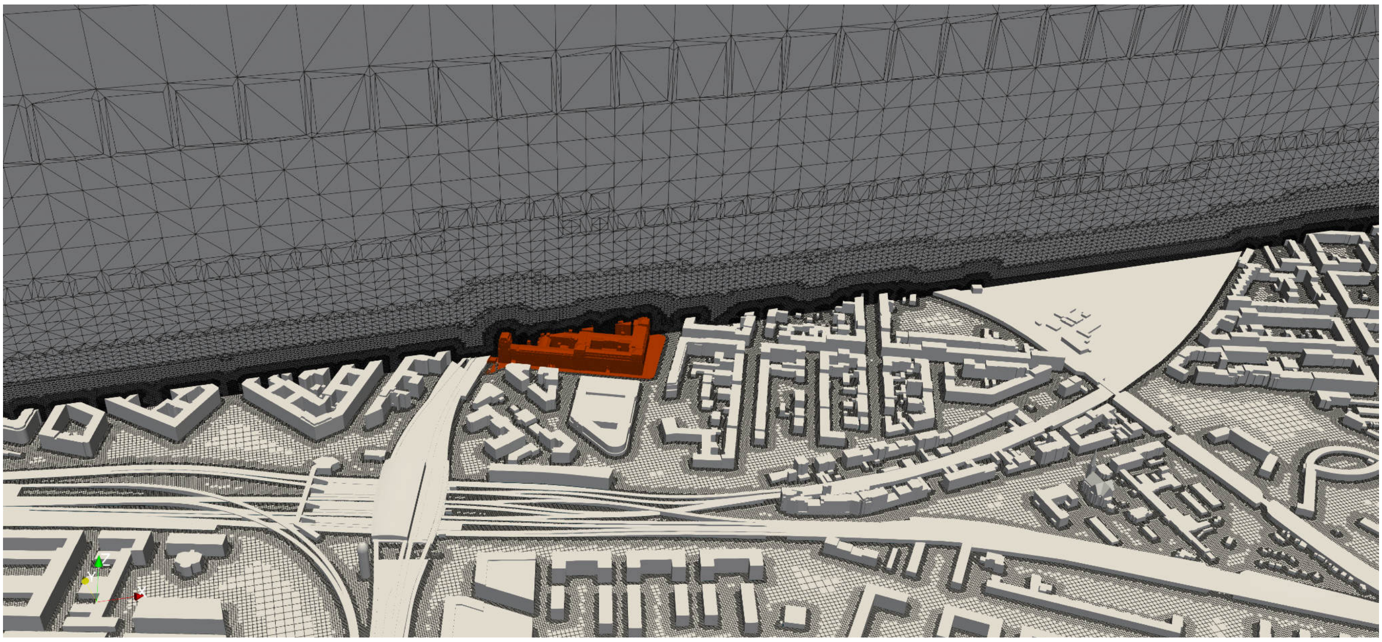


Figure 4.8: Computational grid, view from the side (69.7 Million cells)

In this study focused on pedestrian wind comfort, a rigorous meshing strategy is vital for the calculation of the computational grid, ensuring both the accuracy and reliability of the Computational Fluid Dynamics simulations. The meshing process discretizes the geometry into finite elements, allowing for the numerical solution of fluid flow equations within a defined domain. Employing a hybrid approach, the mesh is finely calibrated near the building's surface and pedestrian zones, while adopting a coarser mesh in areas less pivotal to the study.

The computational grid (mesh) density undergoes a balancing act between computational efficiency and simulation fidelity. A series of mesh independence tests serve as a quality check to validate that the mesh captures critical wind behavior while keeping computational costs in check. Monitoring the velocity magnitude at various points within the computational domain, these tests are incremental; the mesh starts coarse and undergoes successive refinements. Despite some points not fully converging, the observed level of convergence meets the study's accuracy criteria, as supported by Figure 4.9. The final mesh, comprising around 69.7 million cells, serves as a robust foundation for further studies.

The following guidelines were followed while generating the grid:

- A cell ratio of about 1:1:1 in the area of interest to achieve an optimal surface mesh was maintained.
- Three refinement levels are defined at different distances from the terrain and building surfaces:
- The size of the third cell from the ground is smaller than the evaluation height for pedestrian wind comfort, which is typically around 2 m.

Figure 4.8 showcases the resulting computational grid used for the simulation, consisting of 69.7 million cells. This high-resolution mesh is calibrated for accuracy in regions of interest, such as near buildings, while optimizing computational time.

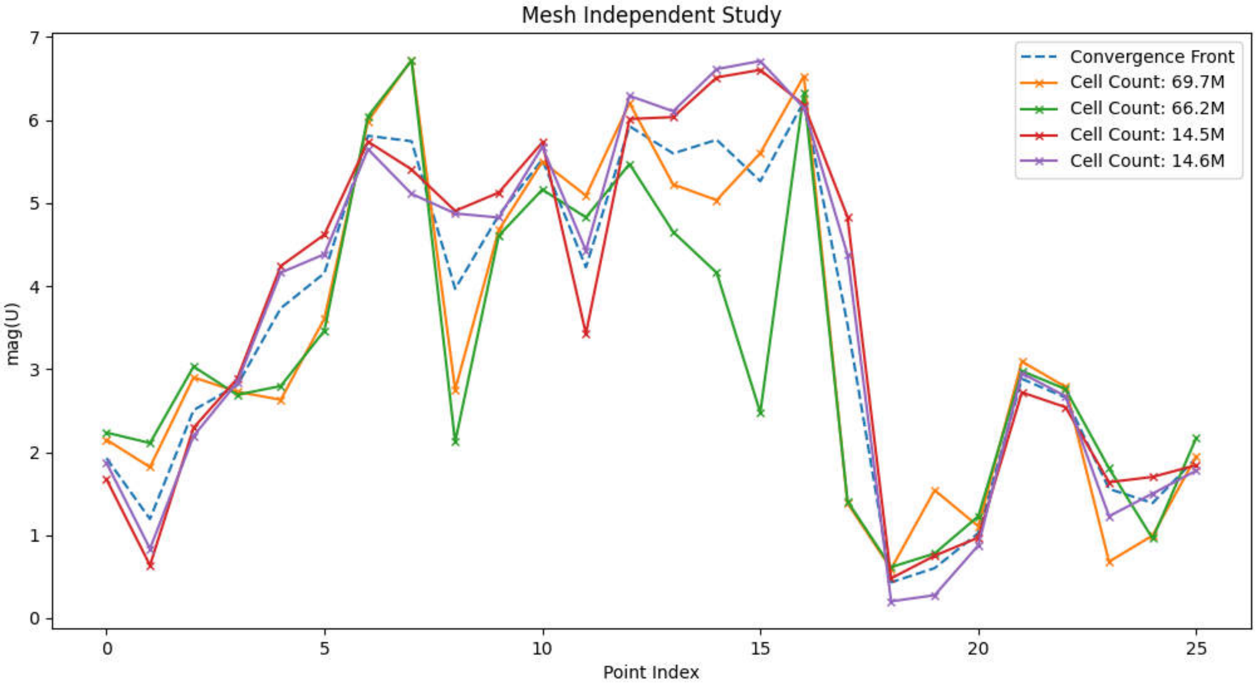


Figure 4.9: Mesh Independence Study illustrating the convergence of the solution for increasing cell counts (Case with wind from west)

4.6. Simulation Setup

4.6.1. Atmospheric Boundary Layer

The Atmospheric Boundary Layer (ABL) is the lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface. It is in the ABL that we experience weather conditions and where structures, like buildings, interact with wind flow.

Figure 4.10: Wind Velocity Profile

For the simulation setup, a custom log-law function was implemented to handle the inlet boundary conditions. This implementation is aligned with Eurocode standards for ground-normal inflow conditions concerning wind velocity and turbulence metrics. The log-law function facilitates the accurate modeling of a homogeneous, two-dimensional, dry-air, equilibrium, and neutral ABL. This approach ensures the simulation's adherence to established European engineering standards, thereby enhancing its accuracy and reliability.

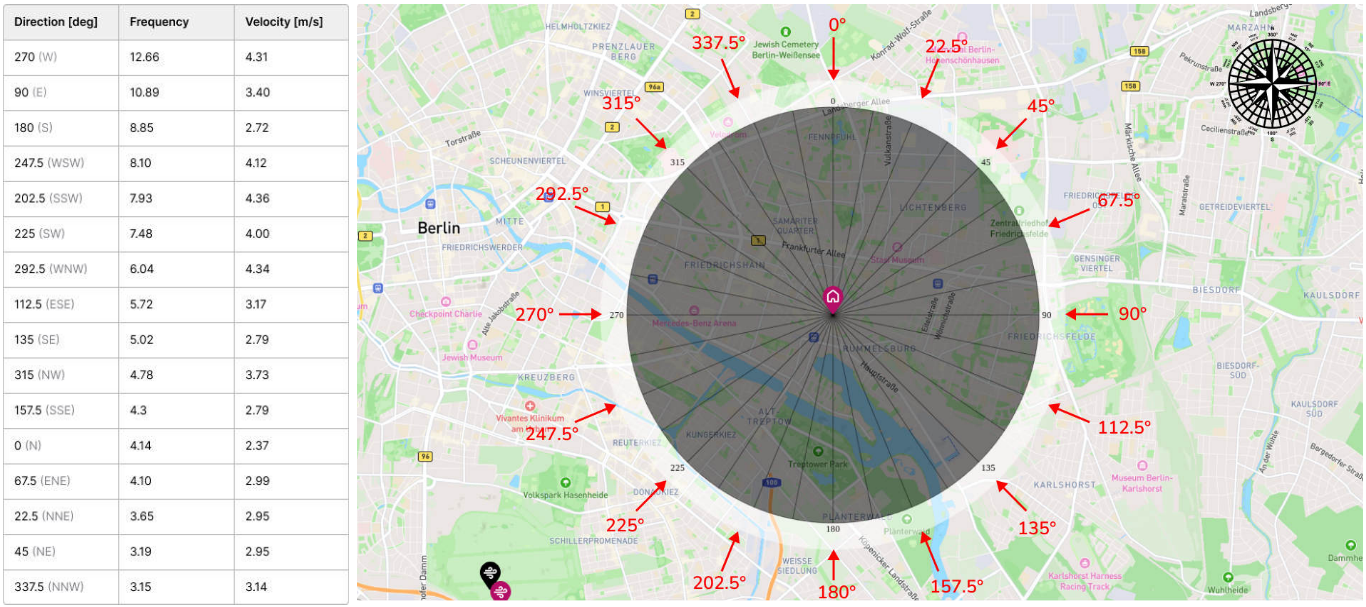
The log-law function is mathematically expressed as:

$$U(z) = \frac{u_*}{\kappa} ln(\frac{z}{z_0})$$

Where $U(z)$ is the wind speed at height z, u_* is the friction velocity, κ is the von Kármán constant (approximately 0.41), and z_0 is the roughness length. This equation enables precise modeling of wind velocity profiles in accordance with Eurocode standards.

4.6.2. Boundary Conditions

For the inlet boundary conditions, historical weather data from multiple directions (Figure 4.11) were analyzed to construct a representative Atmospheric Boundary Layer (ABL) profile. This approach ensures that the simulation closely mirrors real-world conditions.



Direction [deg]	Frequency	Velocity [m/s]
270 (W)	12.66	4.31
90 (E)	10.89	3.40
180 (S)	8.85	2.72
247.5 (WSW)	8.10	4.12
202.5 (SSW)	7.93	4.36
225 (SW)	7.48	4.00
292.5 (WNW)	6.04	4.34
112.5 (ESE)	5.72	3.17
135 (SE)	5.02	2.79
315 (NW)	4.78	3.73
157.5 (SSE)	4.3	2.79
0 (N)	4.14	2.37
67.5 (ENE)	4.10	2.99
22.5 (NNE)	3.65	2.95
45 (NE)	3.19	2.95
337.5 (NNW)	3.15	3.14

Figure 4.11: Wind directions used in the study

Boundary condition types can be extracted from the following table 4.1:

Patch	Boundary Condition Type
inlet	Atmospheric Boundary Layer
outlet	Zero Gradient / Fixed Pressure
top	Symmetry
ground	Rough Wall (Wall function)
buildings	Surface roughness: smooth / Velocity: No slip
environment	Surface roughness: smooth / Velocity: No slip

Table 4.1: Overview of boundary condition types for patches in the computational grid

4.7. Other Simulation Parameters

In this study, the simulation parameters are meticulously configured to focus on pedestrian comfort and local wind effects. The steady-state Reynolds-Averaged Navier-Stokes (RANS) equations, paired with the $k - \omega$ turbulence model, provide a balance between computational efficiency and accuracy. Further precision is achieved through the use of second-order discretization schemes. Preliminary test runs were conducted to optimize time steps and convergence criteria, ensuring both computational efficiency and result reliability. These selections are encapsulated in Table 4.2, which provides an overview of the simulation parameters.

Parameter	**Value**
Equations	Finite Volume / RANS
Solver	simpleFoam (incompressible steady-state)
Turbulence model	$k - \omega$
Discretization schemes	2nd-order

Table 4.2: Overview of Simulation Parameters

To deepen the robustness and real-world applicability of the study, multi-directional wind data for 16 distinct wind directions and their corresponding exceedance wind speeds are incorporated. The Atmospheric Boundary Layer (ABL) is used for the inlet boundary conditions to mimic realistic wind behavior, while standard wall functions are employed for terrain and buildings. This systematic approach makes the simulation both comprehensive and finely tuned to meet the study's objectives.

5. CFD Results Analysis

5.1. Flow field at 2m height

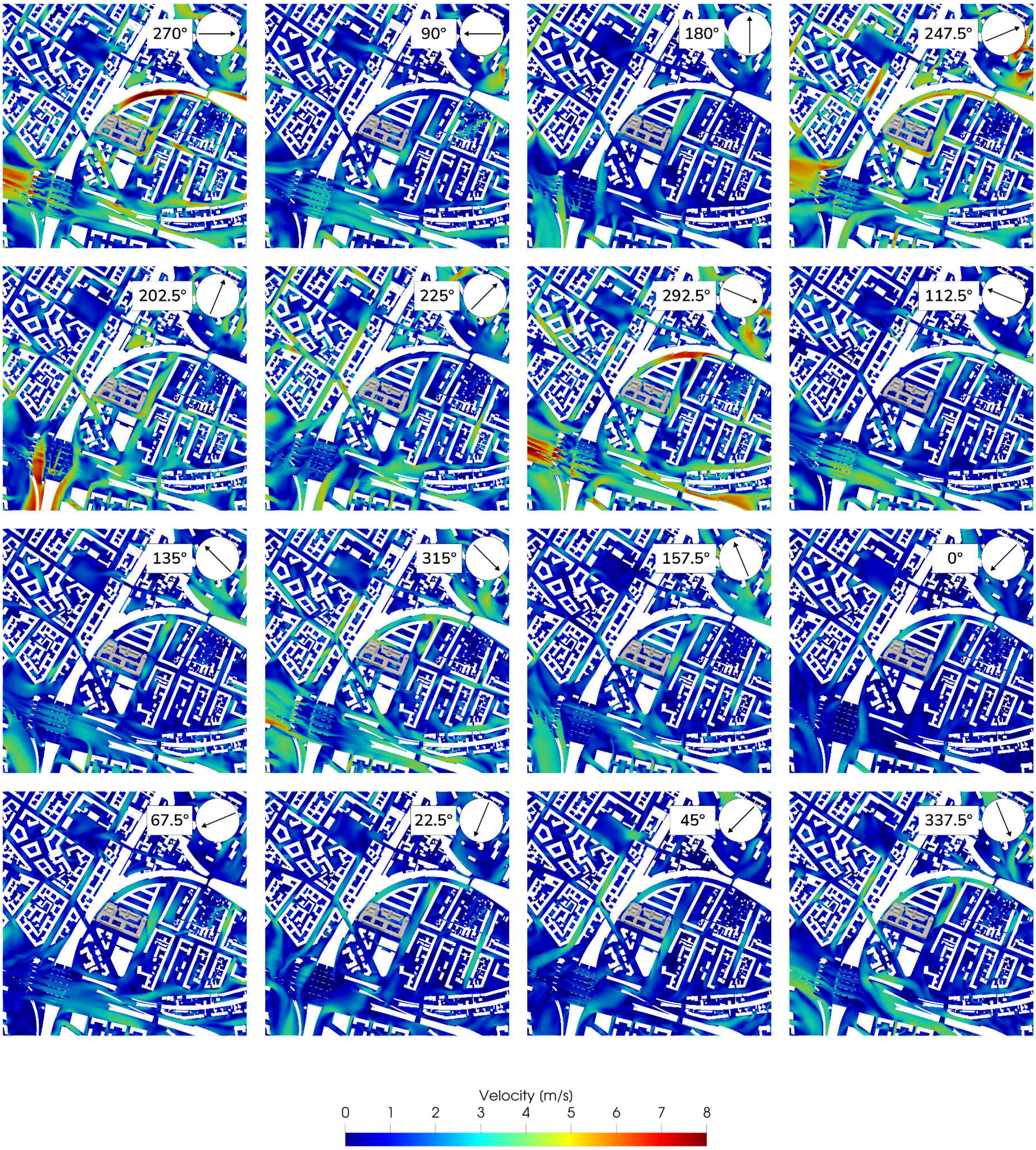


Figure 5.1: Wind velocity at 2 m above ground. All 16 simulations are based on the data taken from the nearby located weather station. The arrow indicates the wind direction.

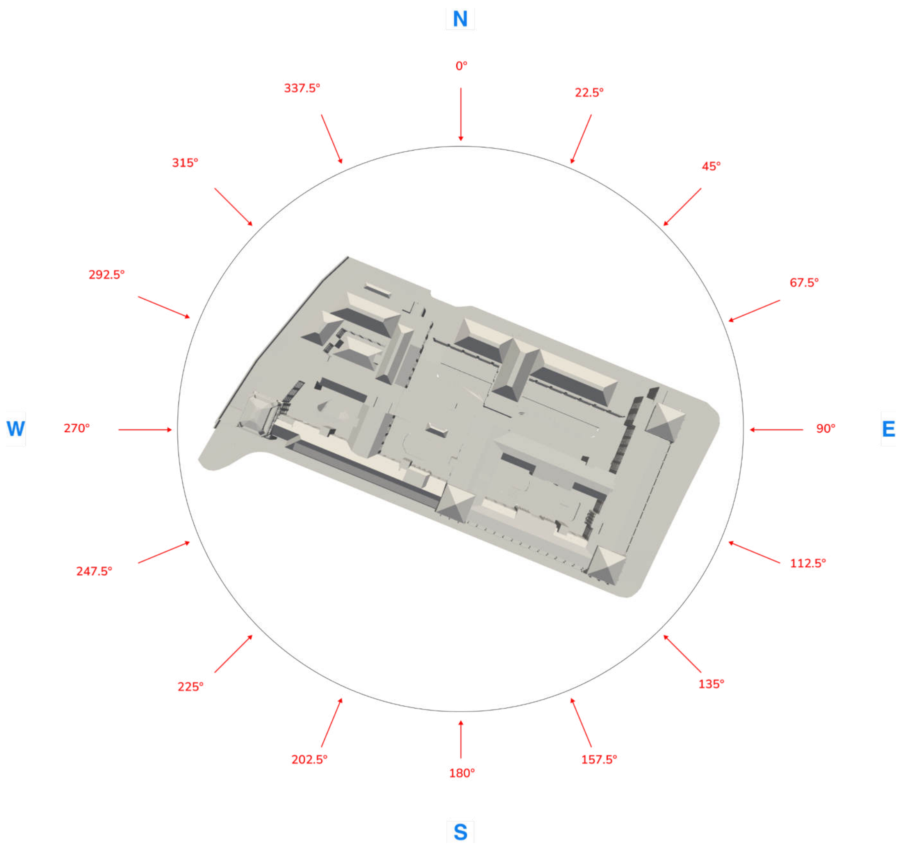


Figure 5.2: Illustration of wind directions related to the building

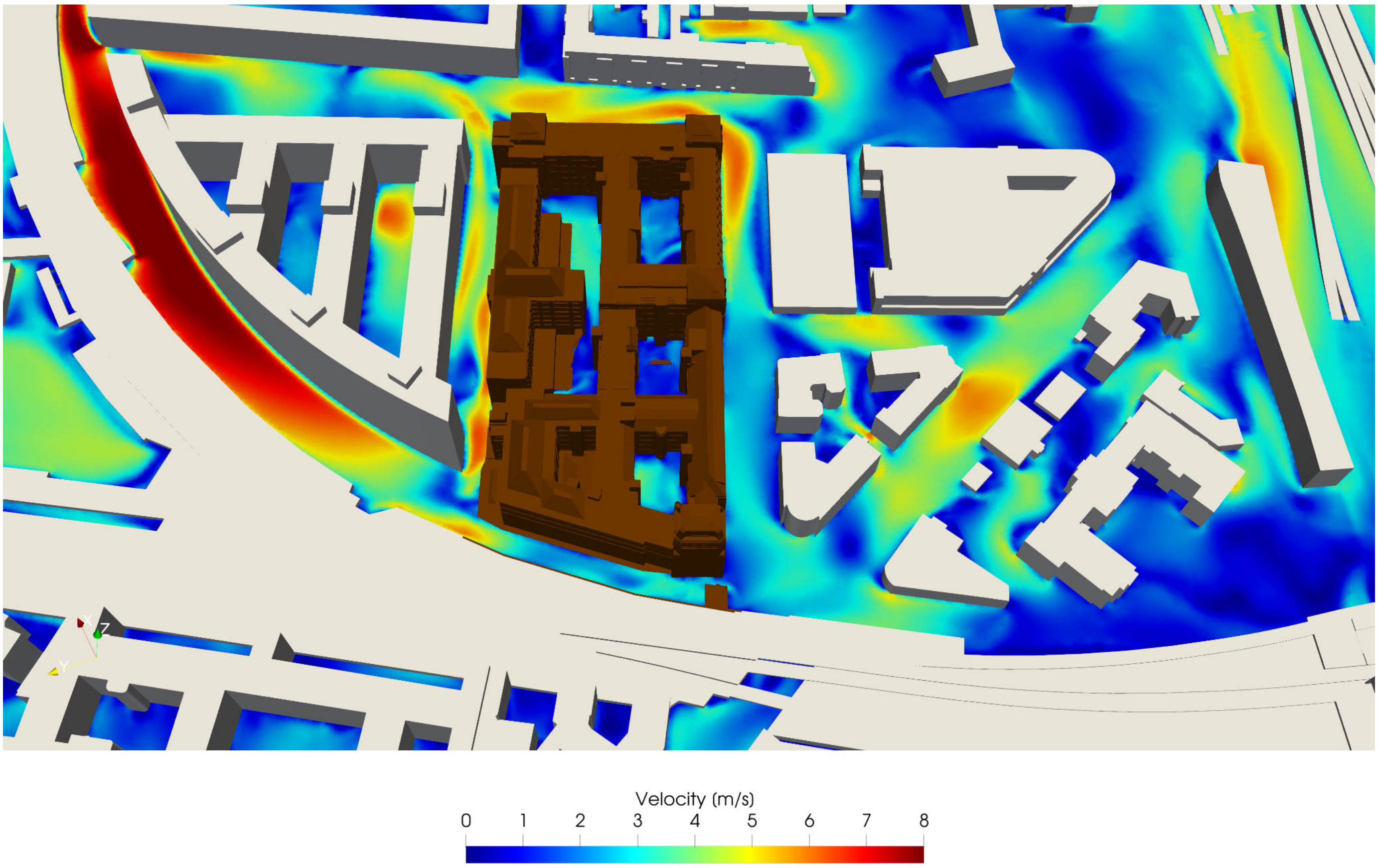


Figure 5.3: Wind velocity at 2 m above ground, wind from 270°

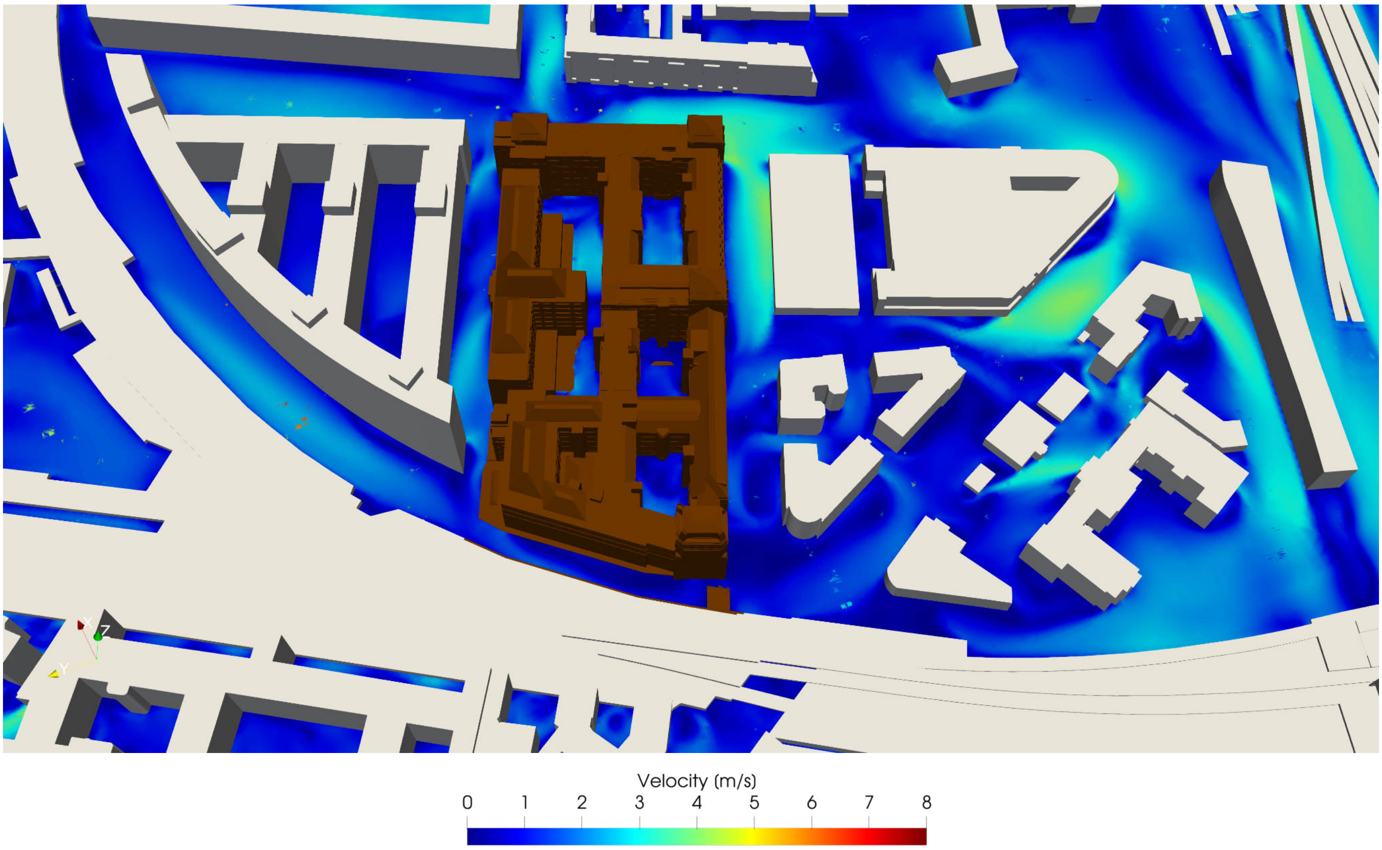


Figure 5.4: Wind velocity at 2 m above ground, wind from 90°

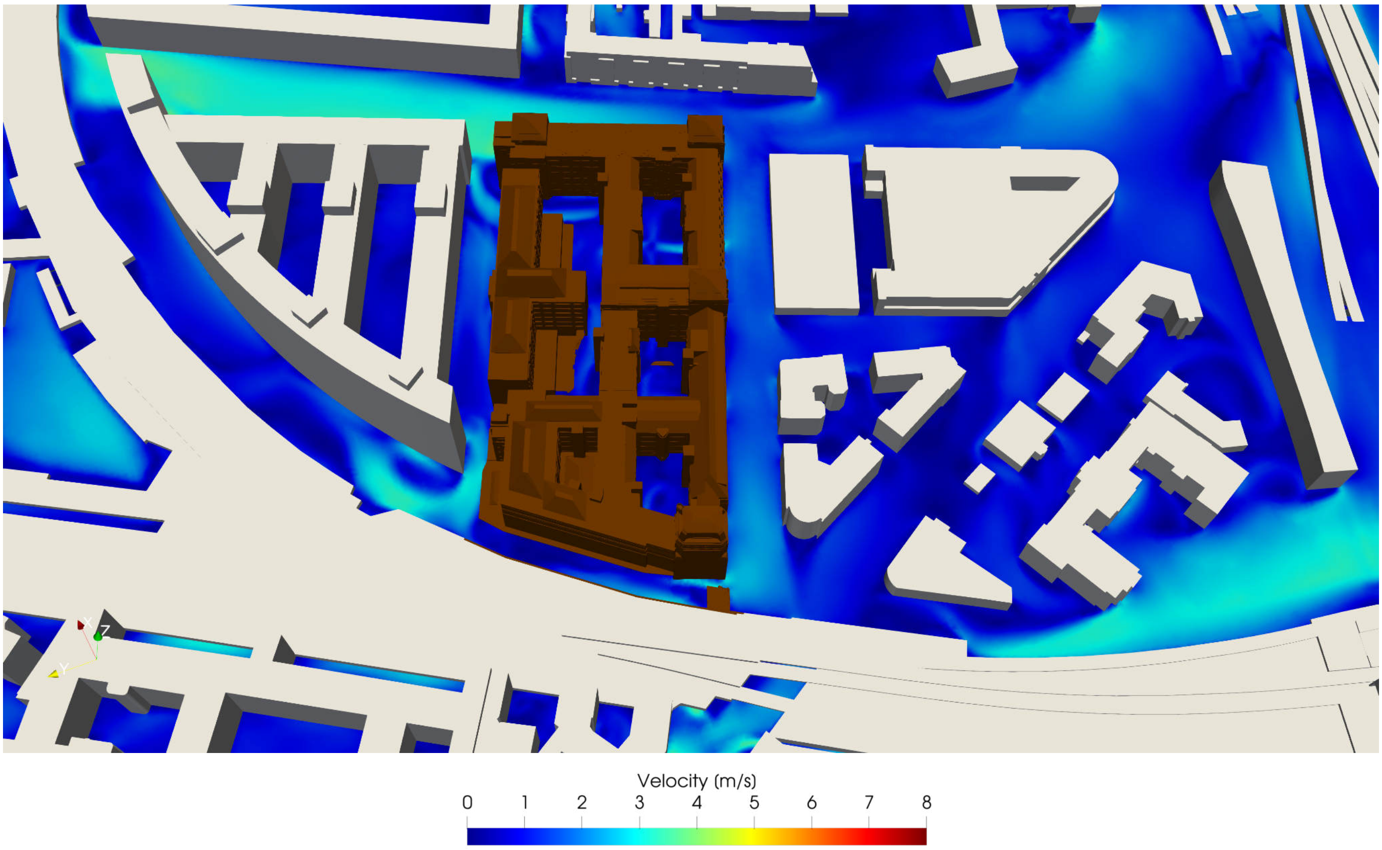


Figure 5.5: Wind velocity at 2 m above ground, wind from 180°

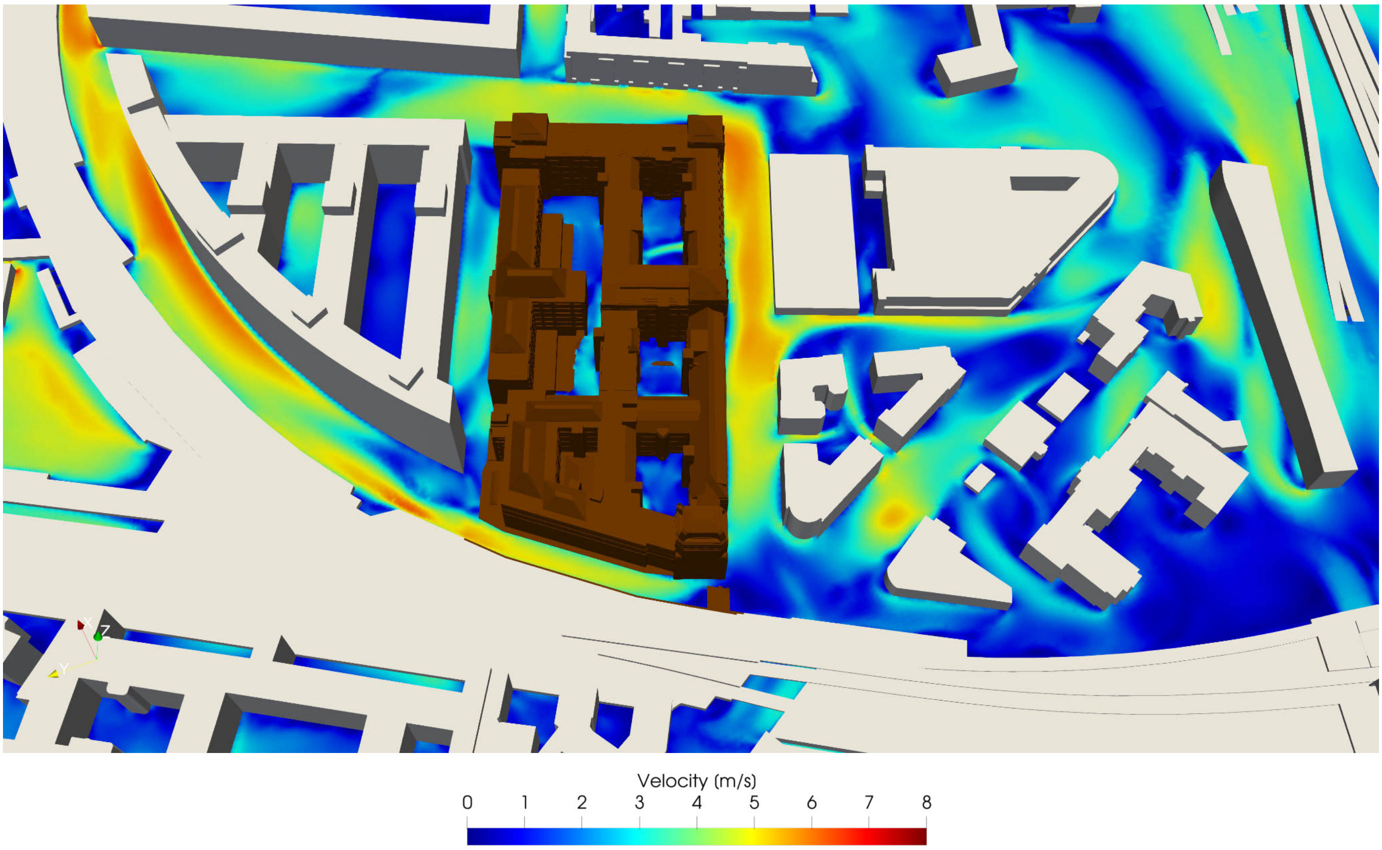


Figure 5.6: Wind velocity at 2 m above ground, wind from 247.5°

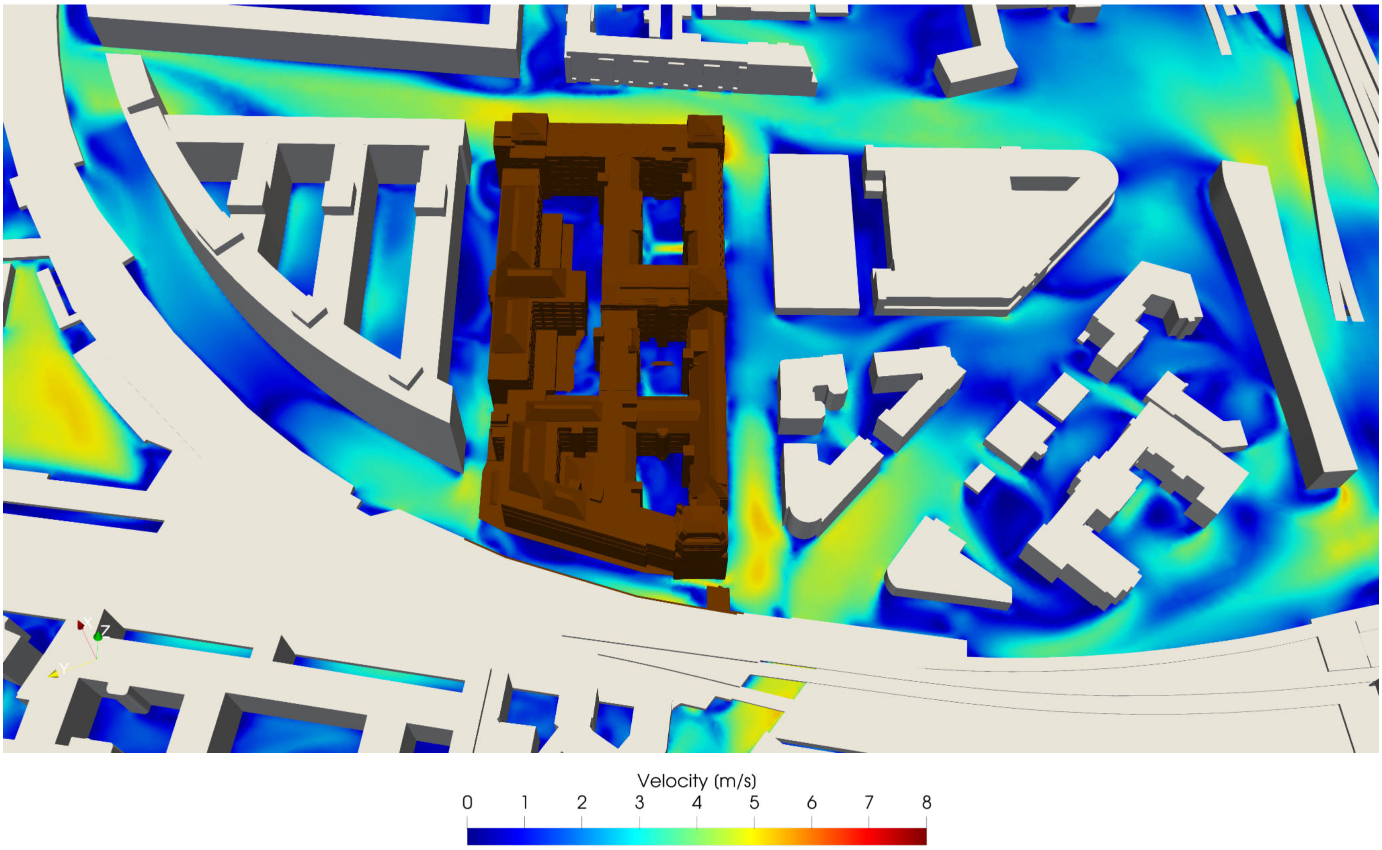


Figure 5.7: Wind velocity at 2 m above ground, wind from 202.5°

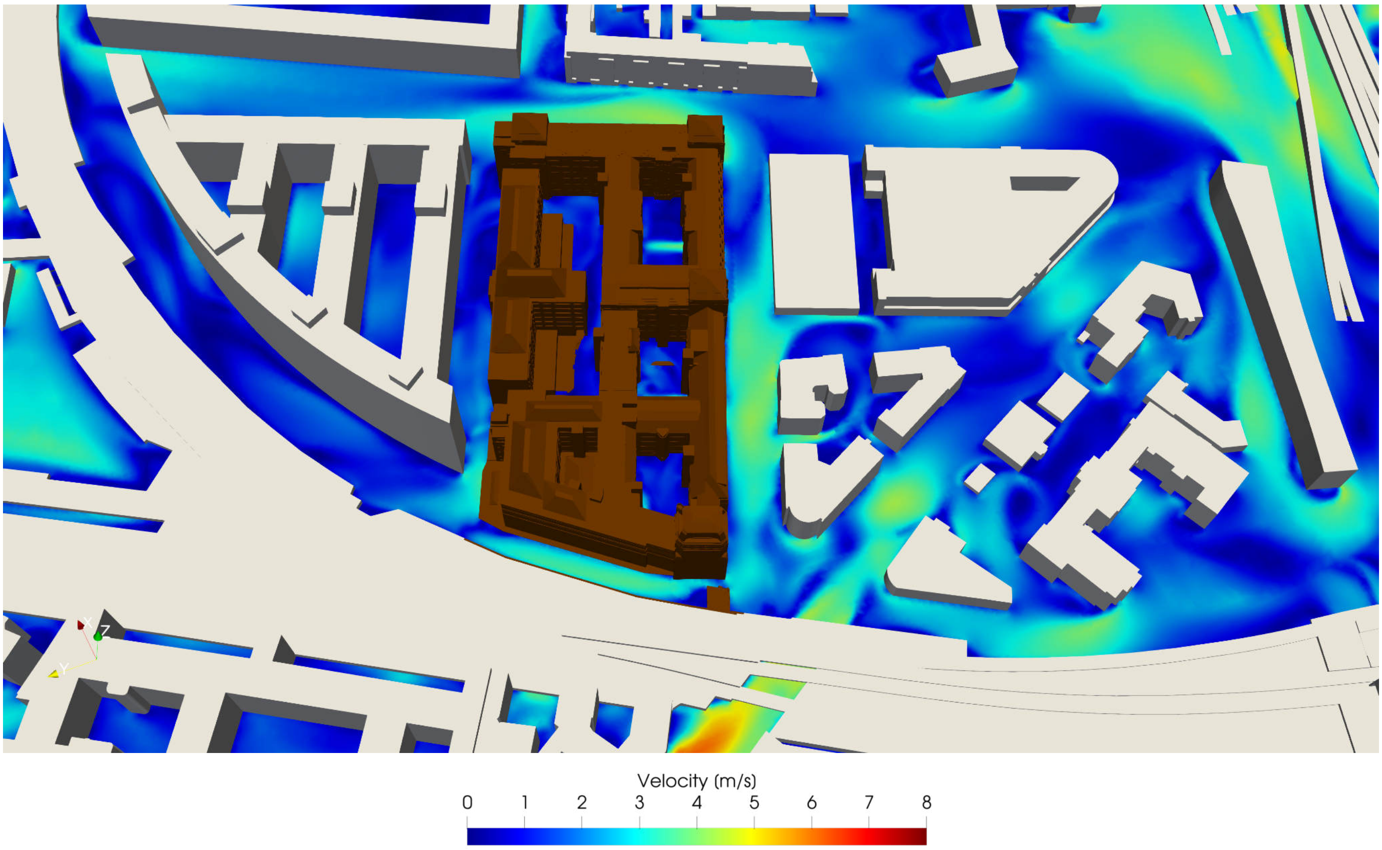


Figure 5.8: Wind velocity at 2 m above ground, wind from 225°

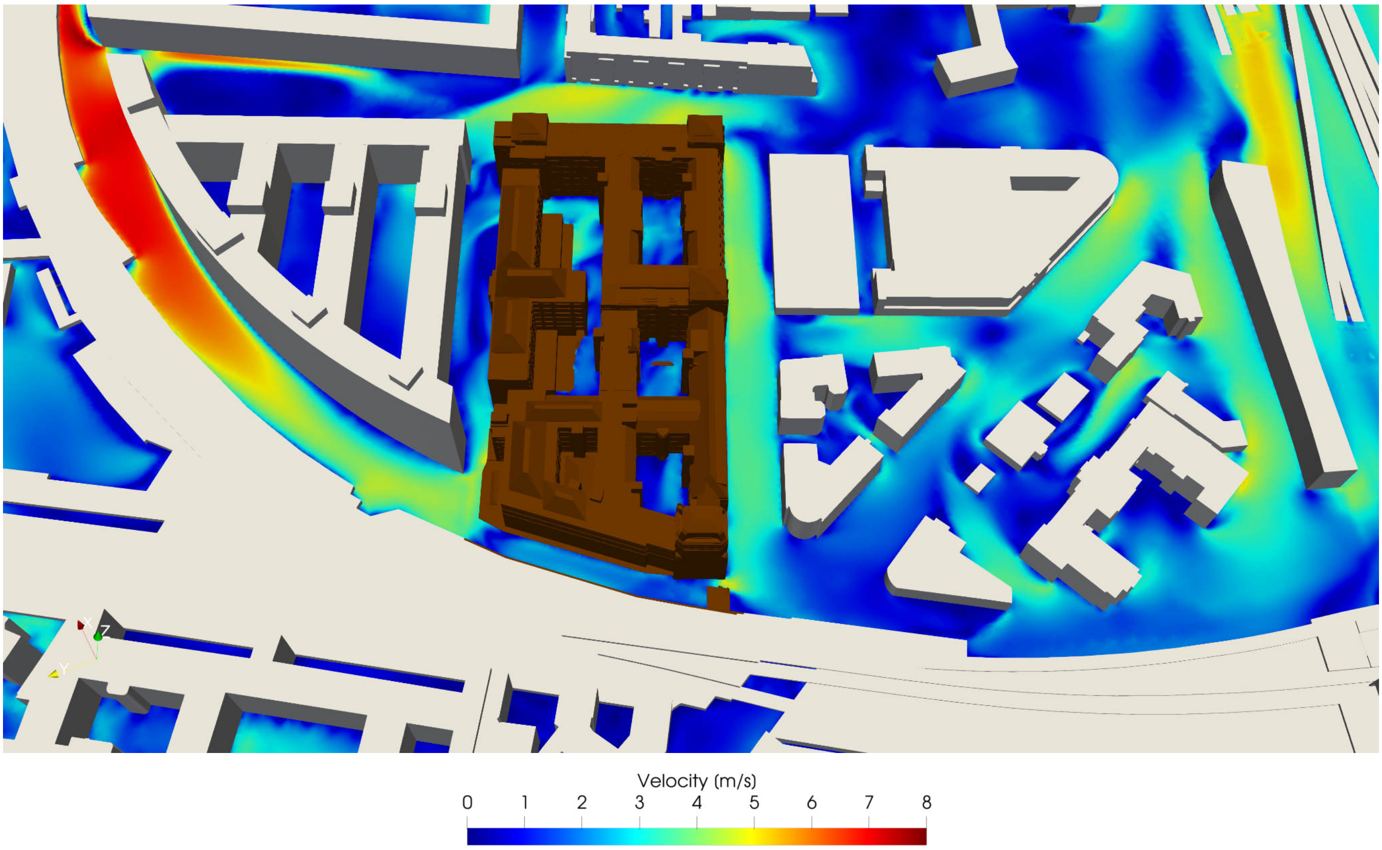


Figure 5.9: Wind velocity at 2 m above ground, wind from 292.5°

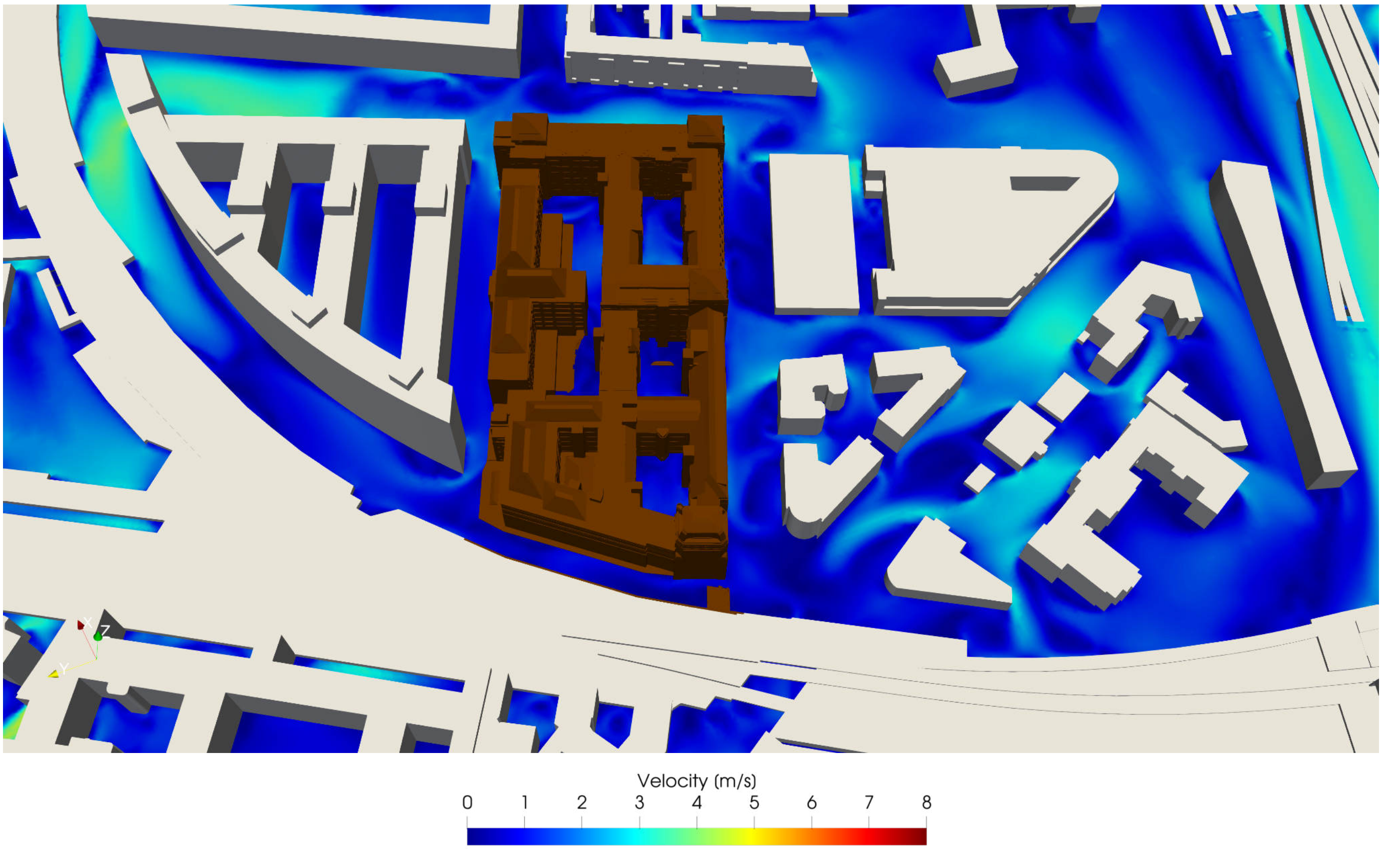


Figure 5.10: Wind velocity at 2 m above ground, wind from 112.5°

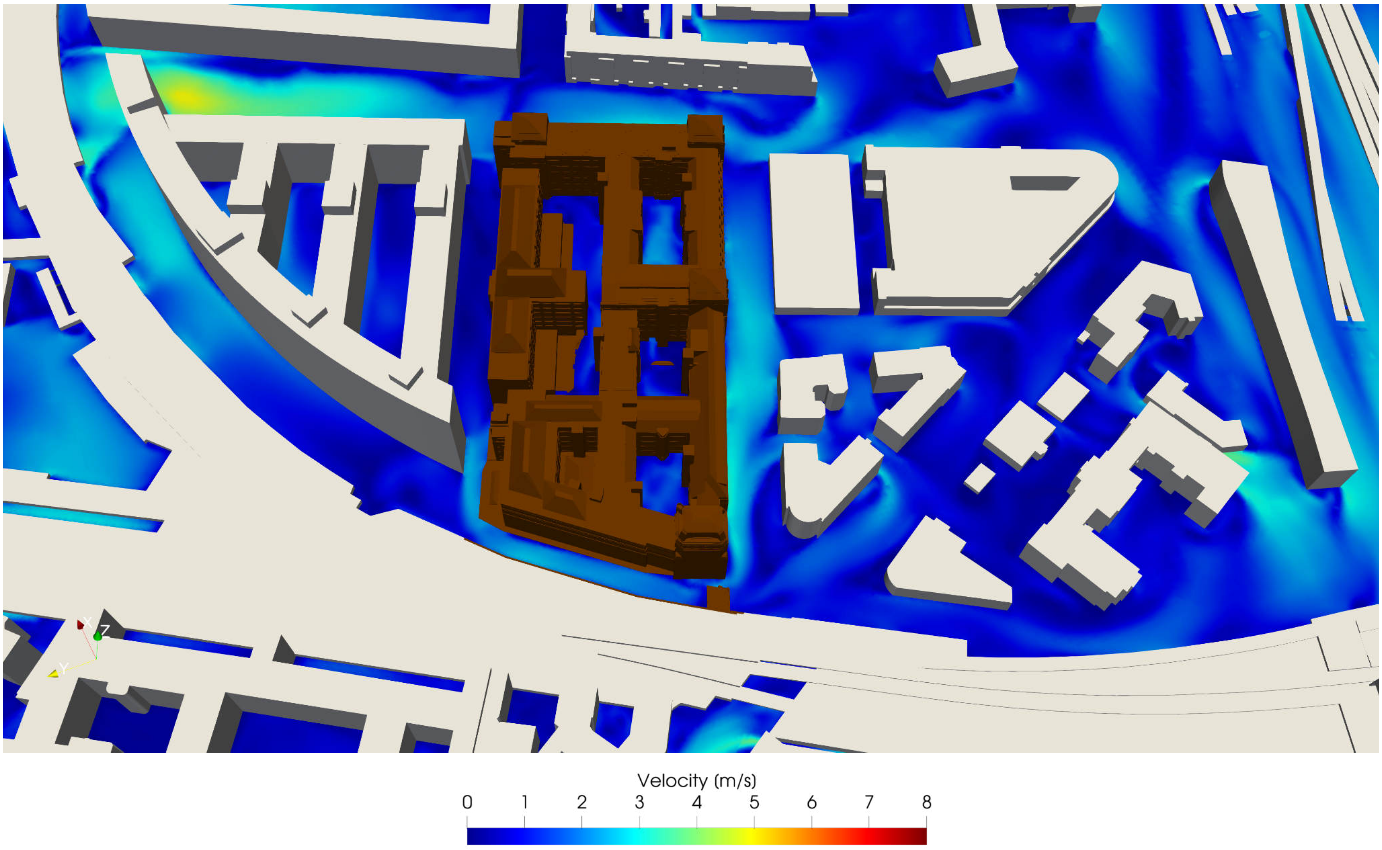


Figure 5.11: Wind velocity at 2 m above ground, wind from 135°

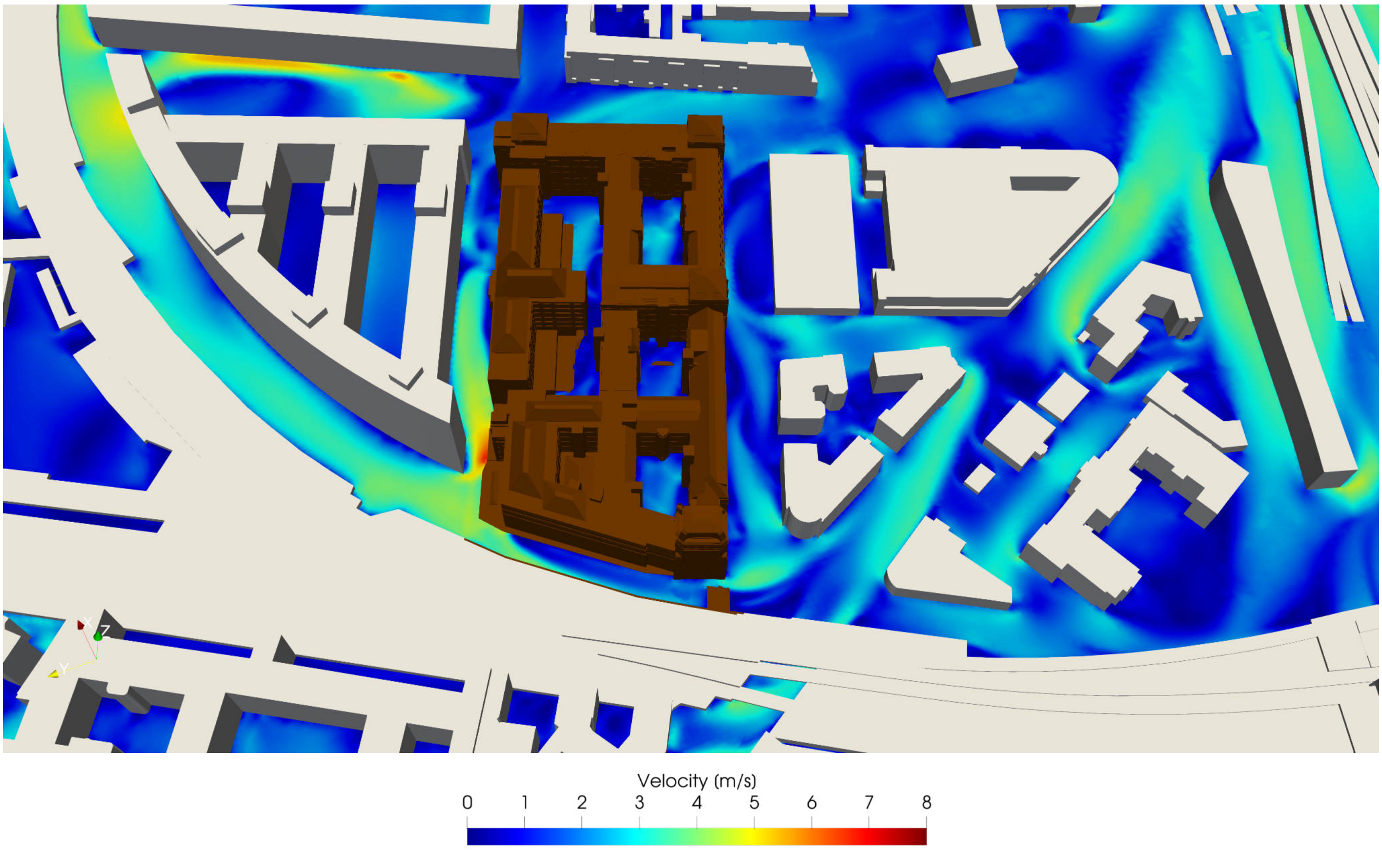


Figure 5.12: Wind velocity at 2 m above ground, wind from 315°

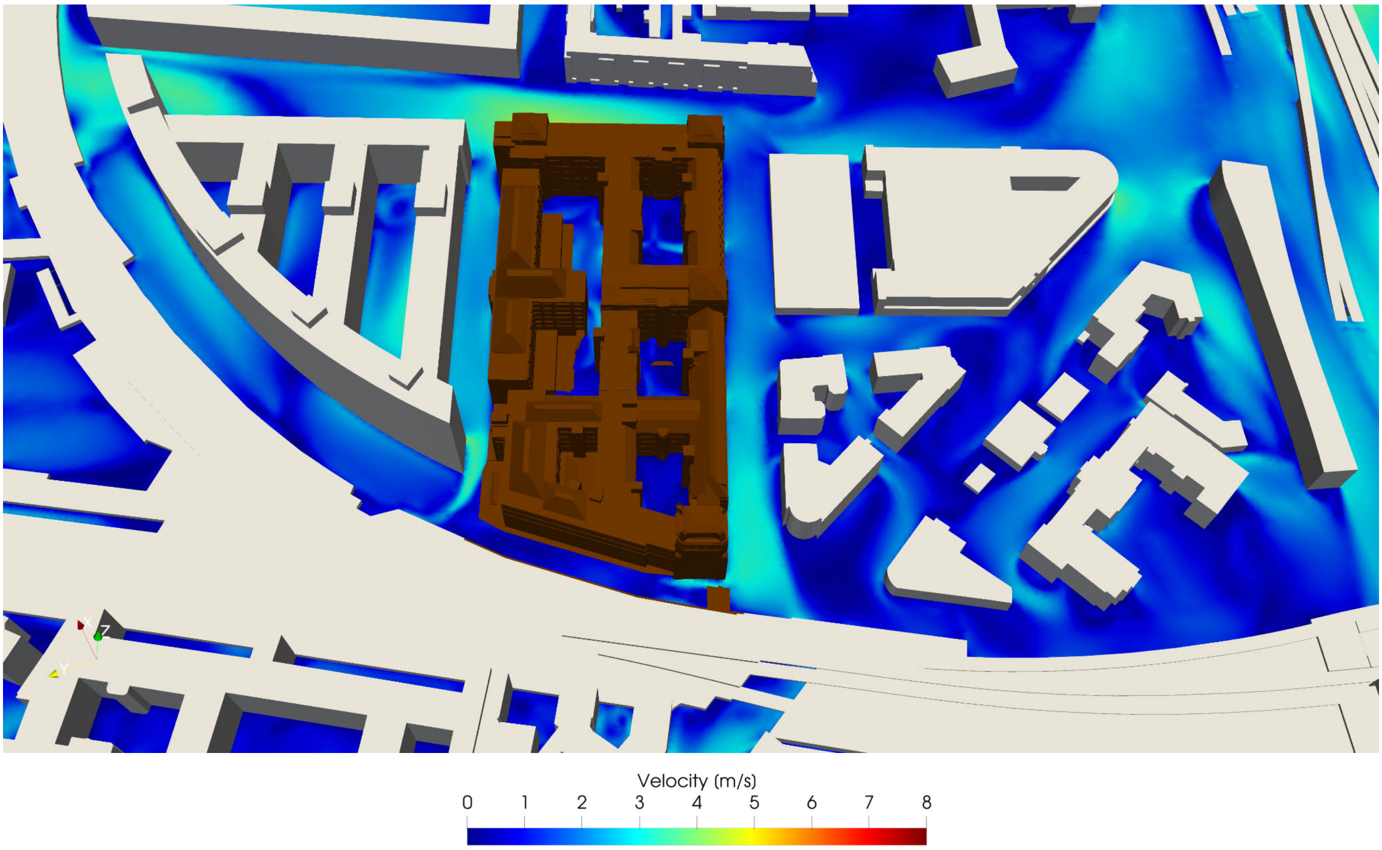


Figure 5.13: Wind velocity at 2 m above ground, wind from 157.5°

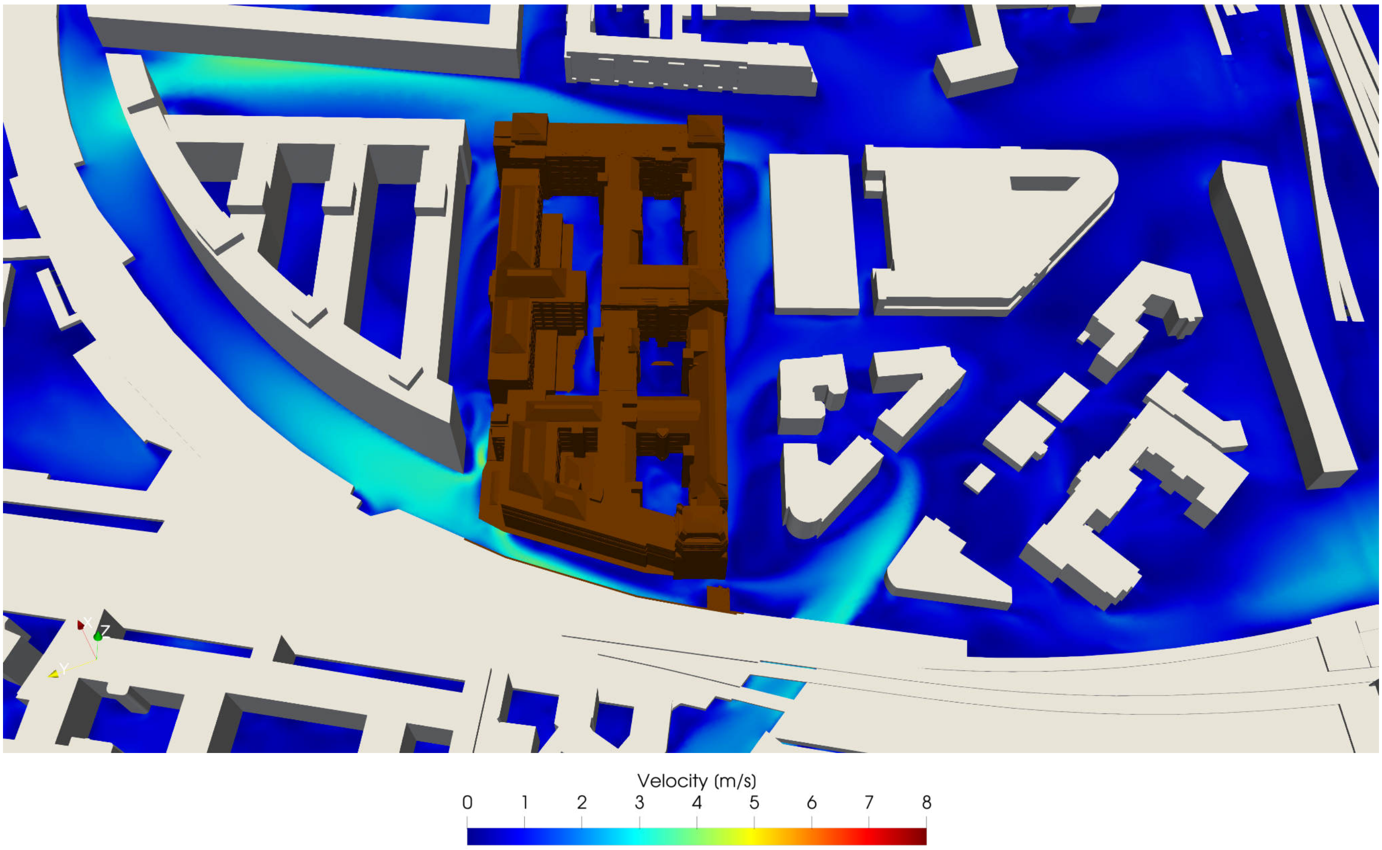


Figure 5.14: Wind velocity at 2 m above ground, wind from 0°

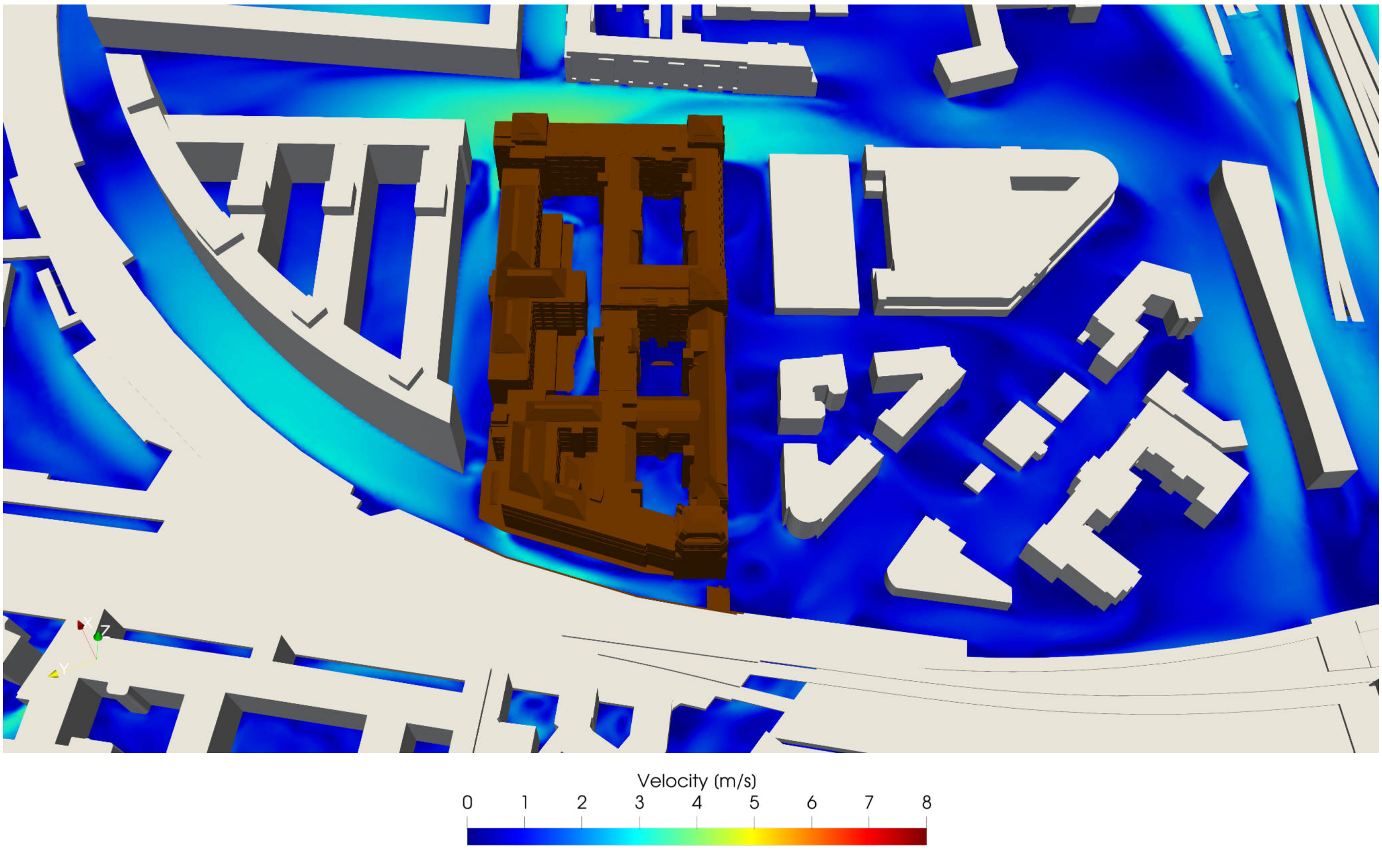


Figure 5.15: Wind velocity at 2 m above ground, wind from 67.5°

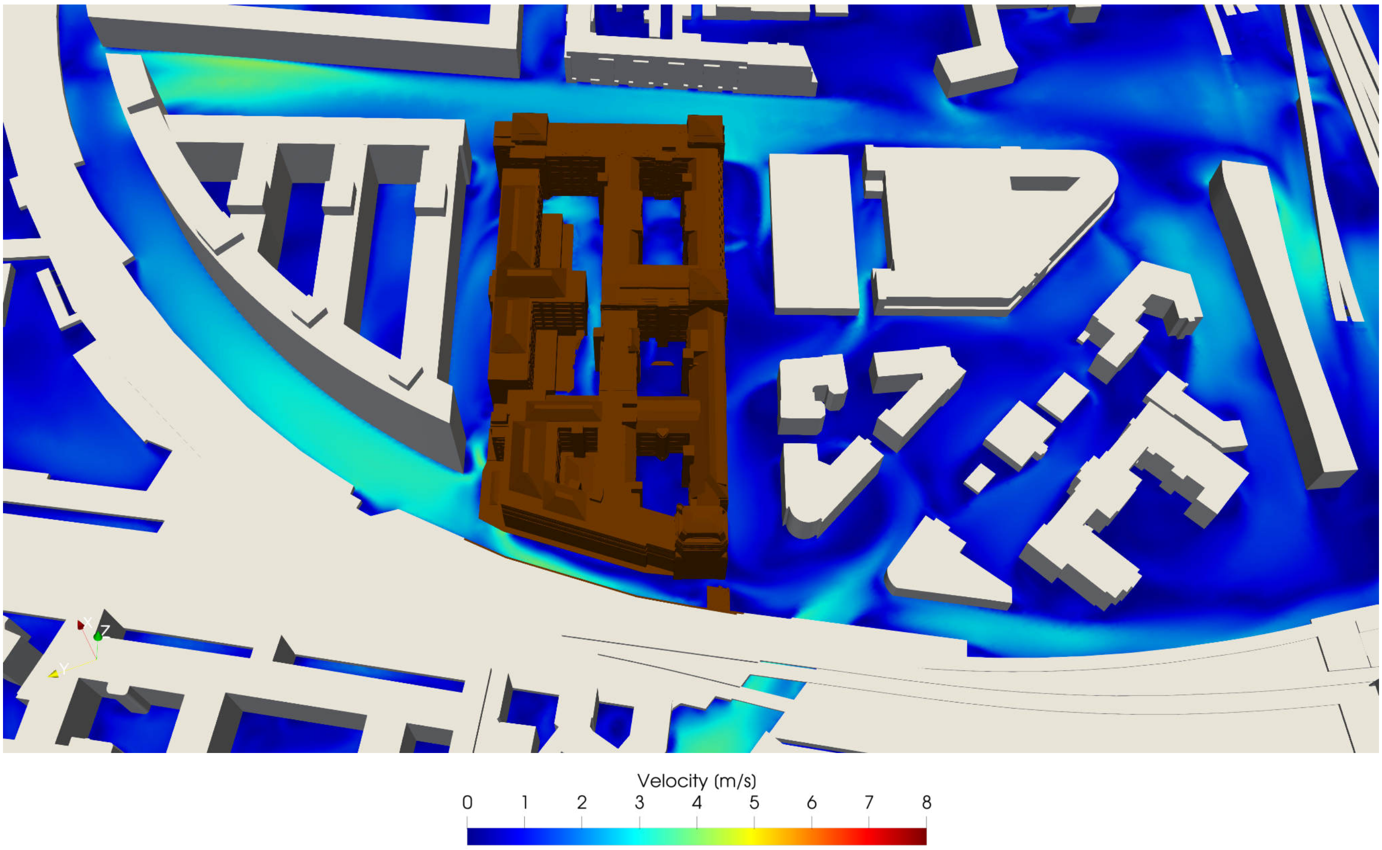


Figure 5.16: Wind velocity at 2 m above ground, wind from 22.5°

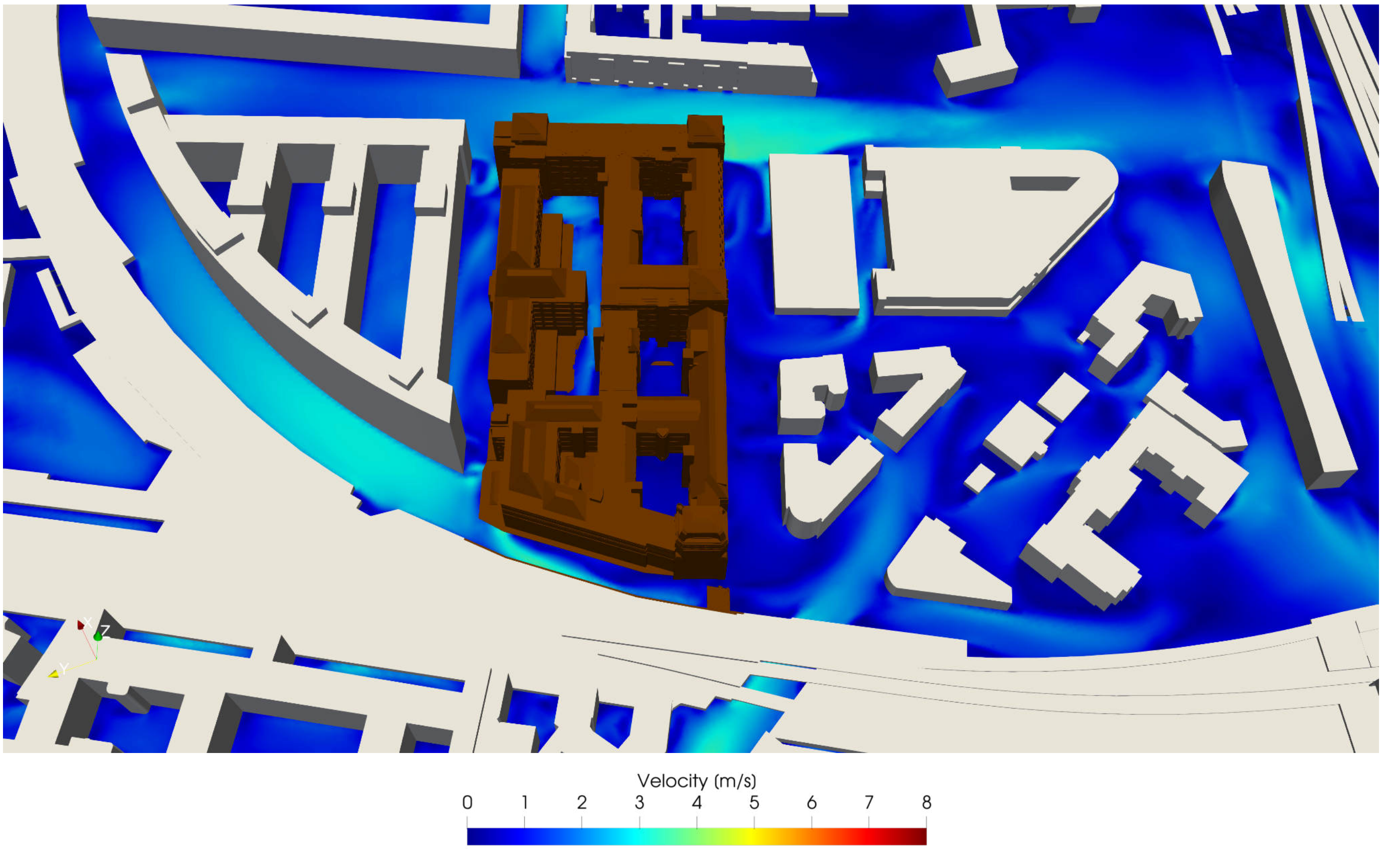


Figure 5.17: Wind velocity at 2 m above ground, wind from 45°

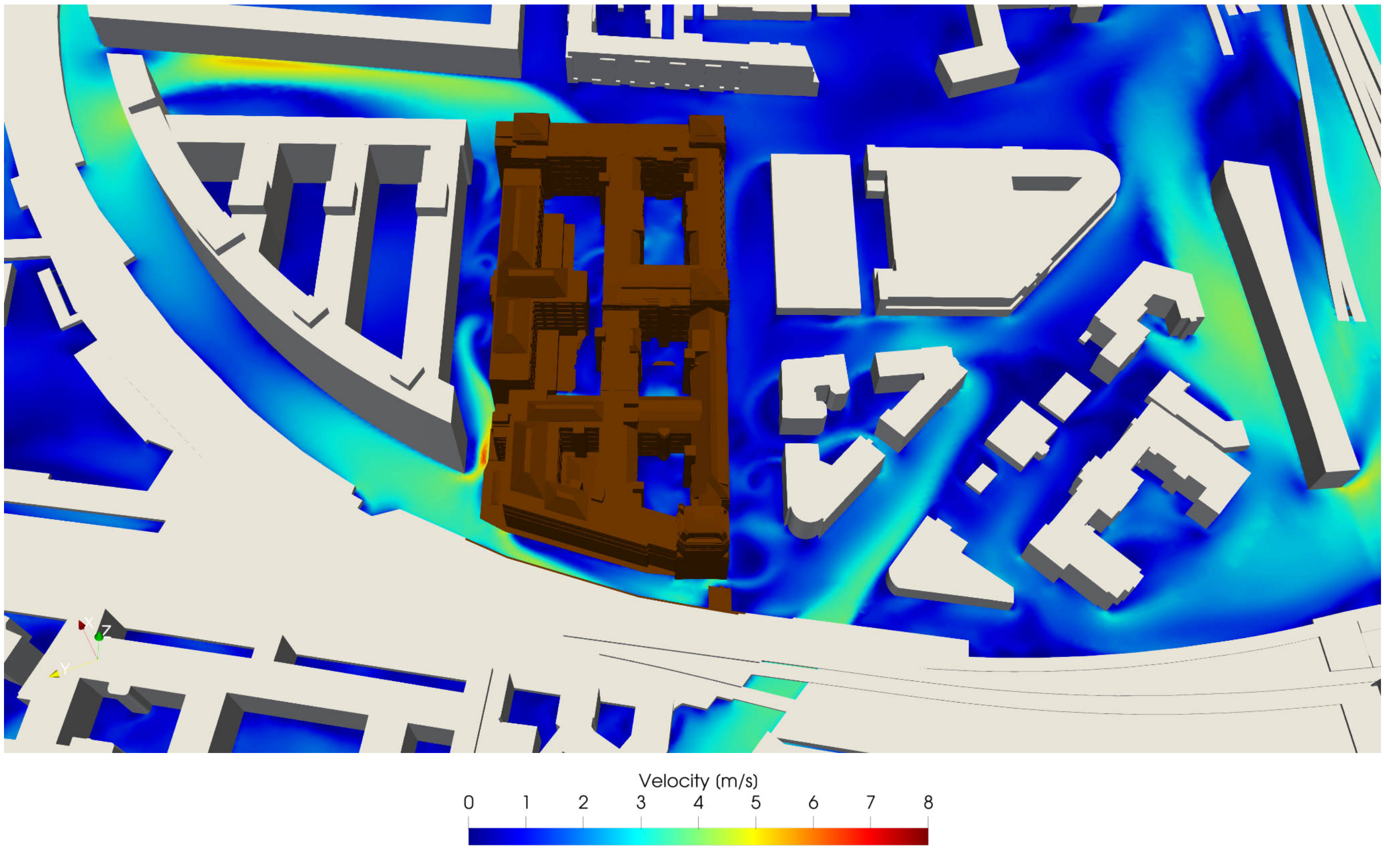


Figure 5.18: Wind velocity at 2 m above ground, wind from 337.5°

CFD results for velocity magnitudes at 2m above ground level across all 16 wind directions are displayed in Figures 5.1 and 5.3 to 5.18. A relatively small number of scenarios exhibit high wind speeds due to phenomena such as corner acceleration or tunneling. In these visualizations, red denotes high speeds (approximately 8 m/s) and blue low speeds (around 0 m/s).

The necessity for mitigation in these high-speed areas will be further evaluated in a comfort map analysis in the following chapter.

5.2. Pressure coefficient for dominant wind directions

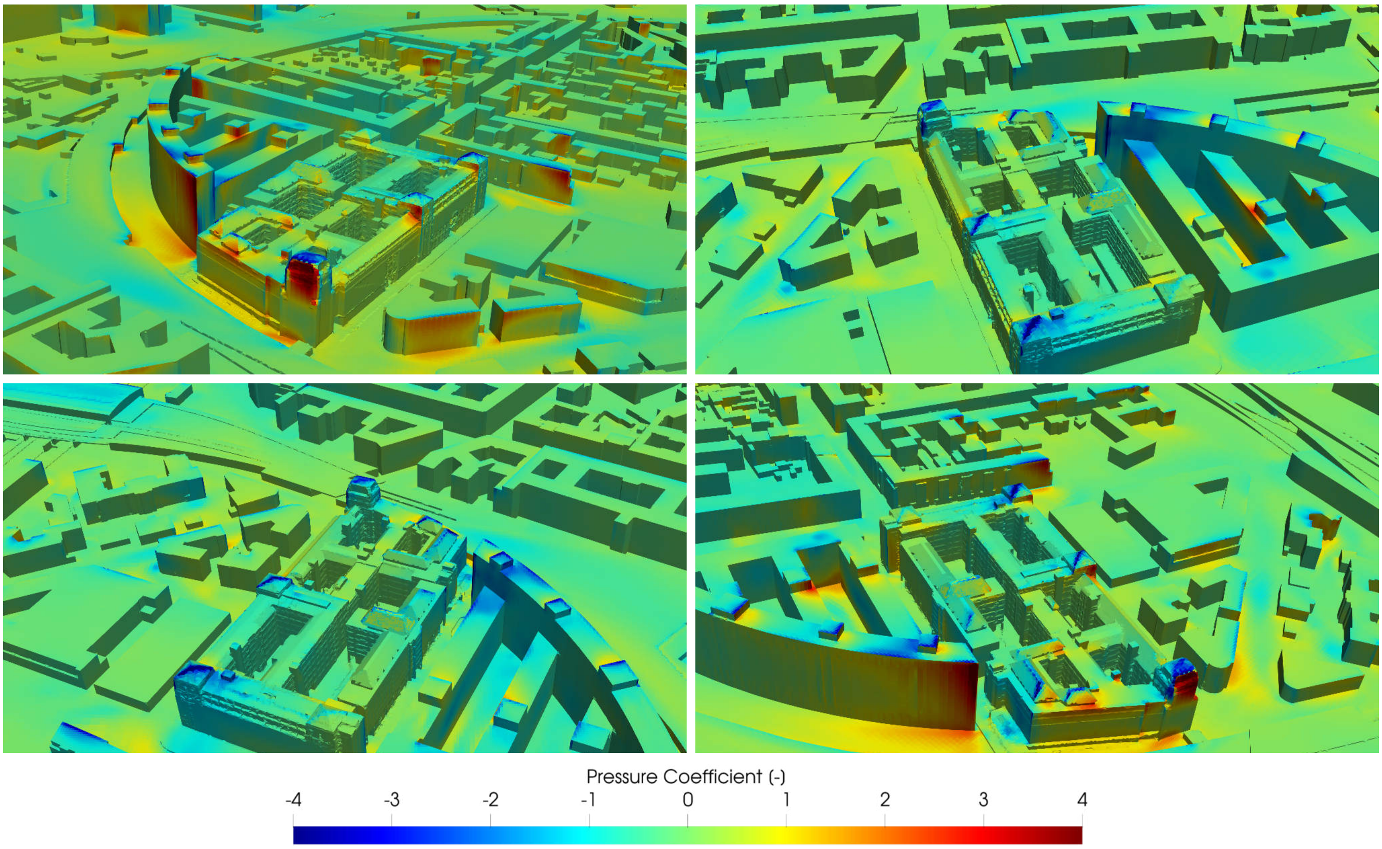


Figure 5.19: Pressure coefficient, wind from 270°

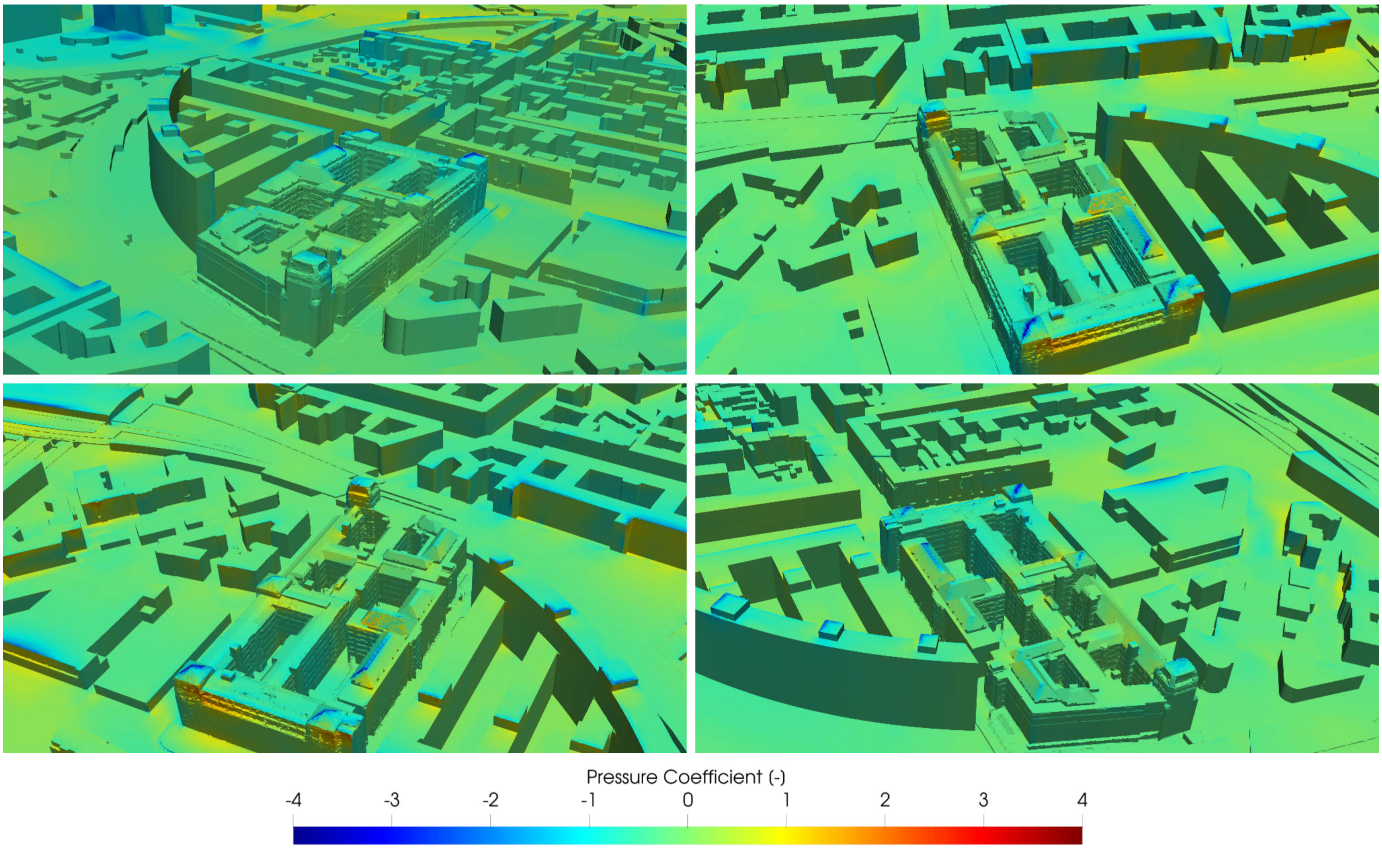


Figure 5.20: Pressure coefficient, wind from 90°

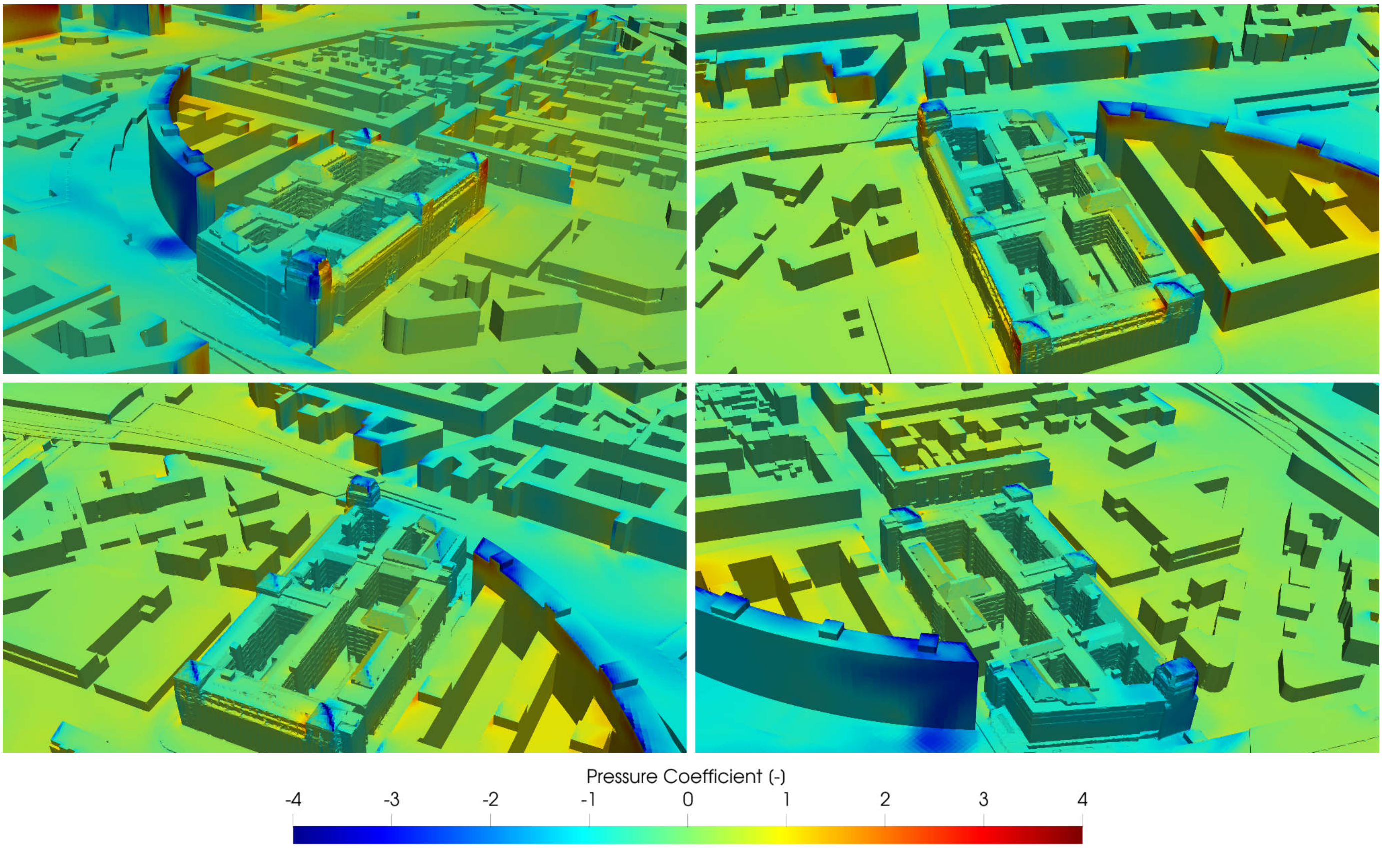


Figure 5.21: Pressure coefficient, wind from 180°

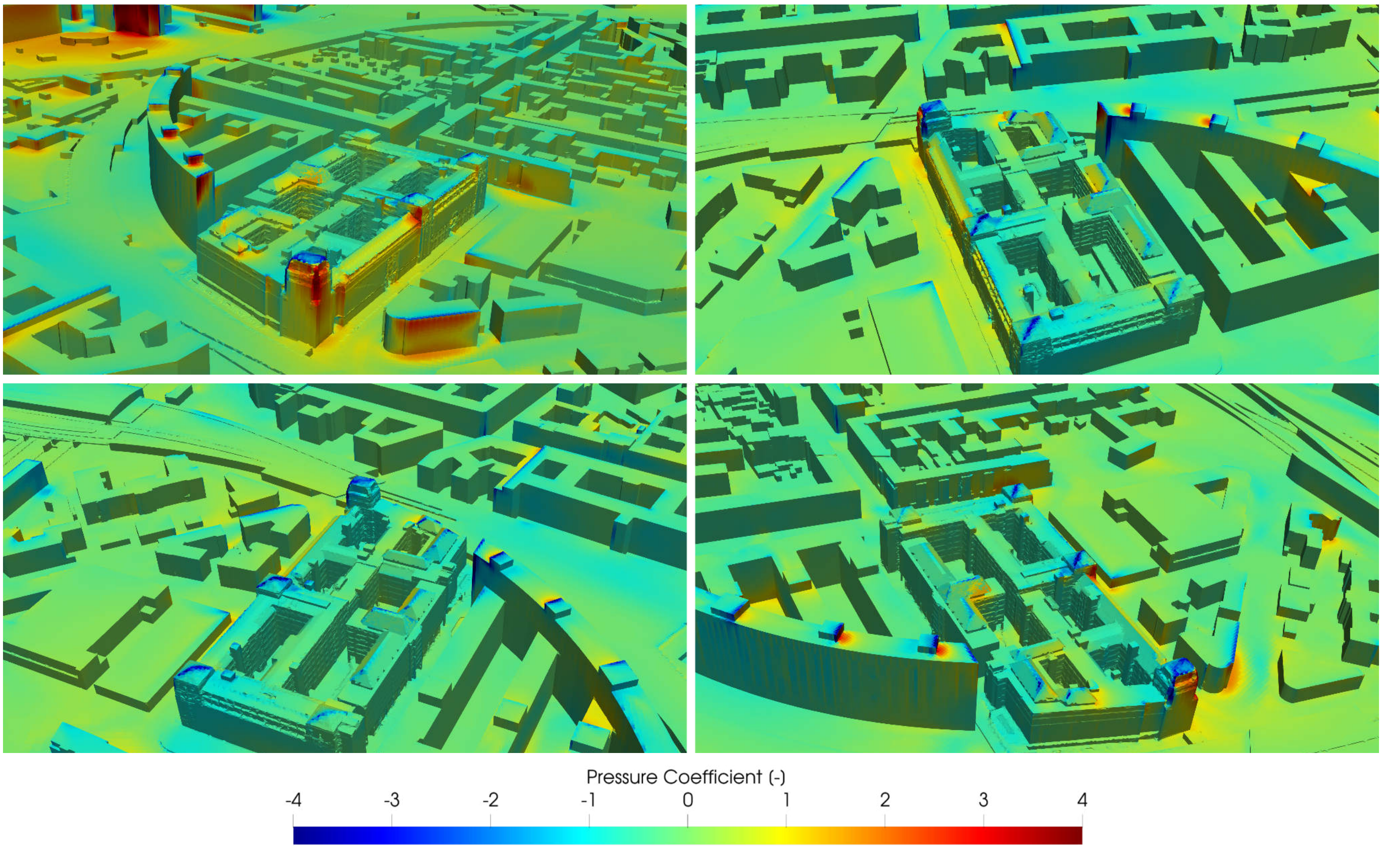


Figure 5.22: Pressure coefficient, wind from 247.5°

Figures 5.19 to 5.22 illustrate the pressure coefficient profiles for the four dominant wind directions. In these visualizations, negative values (depicted in blue) indicate suction forces, while positive values (shown in red) represent pressure forces acting on the building structure. This data can serve as a basis for targeted design recommendations.

5.3. Velocity field and pressure coefficient for extreme weather conditions

In the evaluation of extreme wind conditions, the Generalized Extreme Value (GEV) distribution was employed to pinpoint the maximum wind speed and its originating direction. The data reveals a peak wind speed of 9.72 m/s coming from a 270° direction. This critical information serves as a robust metric for assessing the structural resilience of the Berliner Bremsenwerk complex under extreme wind conditions. Detailed graphical representation of these findings can be found in Figures 5.23 and 5.24.

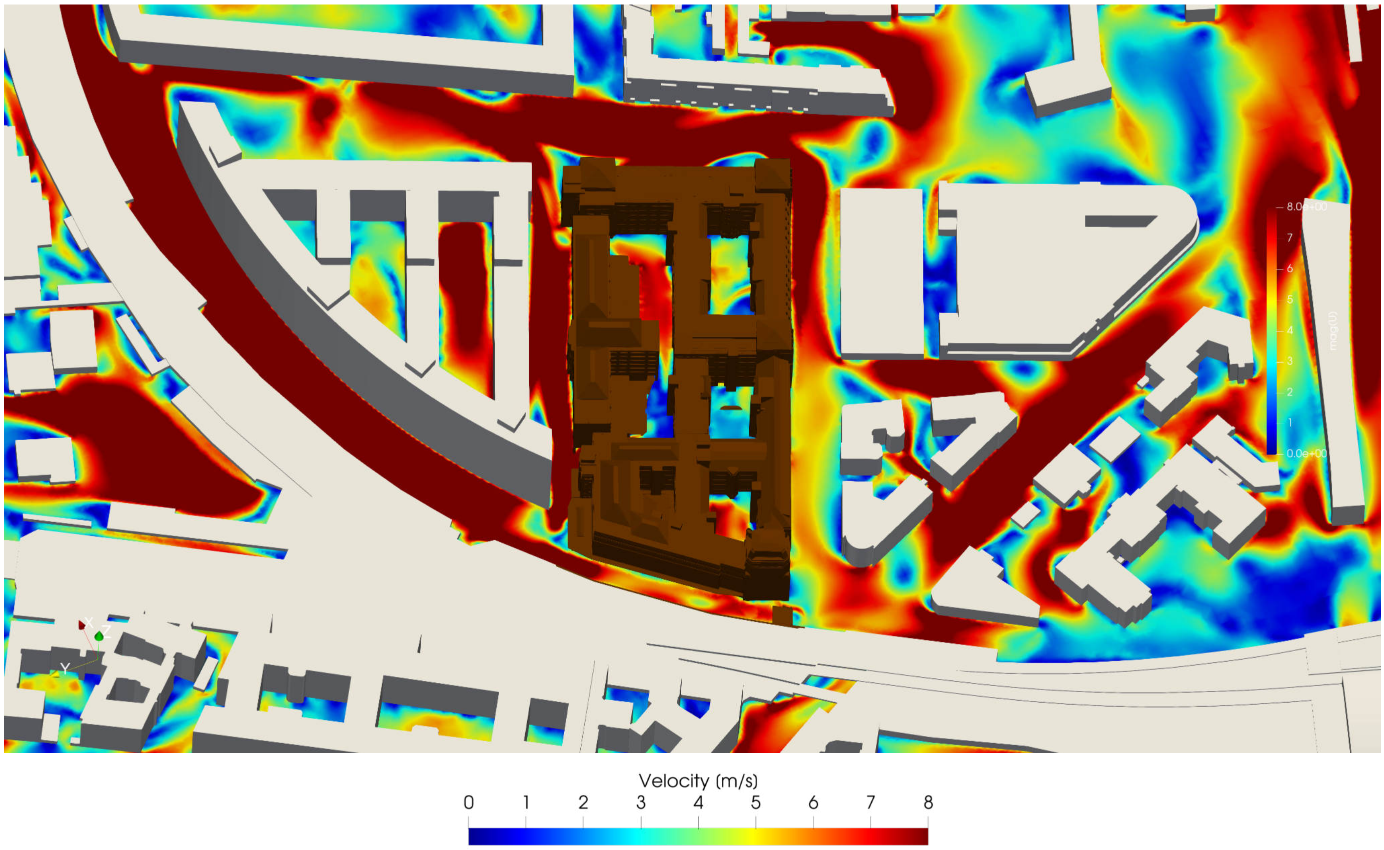


Figure 5.23: Wind velocity at 2 m above ground, wind from 270° (extreme weather conditions)

The velocity field, measured at a height of 2 meters from the ground, shows elevated wind speeds when compared to simulations designed for assessing pedestrian comfort. This escalation is anticipated due to the extreme wind speed benchmark of 9.72 m/s used in the analysis. Although numerous zones around the building perimeter display heightened velocities, these conditions may be tolerable given their brief occurrence.

The marginal variation observed in the pressure coefficient visualization, even under extreme wind conditions, underscores that the building geometry plays a pivotal role in influencing the pressure distribution surrounding the structure. This suggests that the aerodynamic properties of the building are predominantly governed by its geometric design rather than changes in flow velocity.

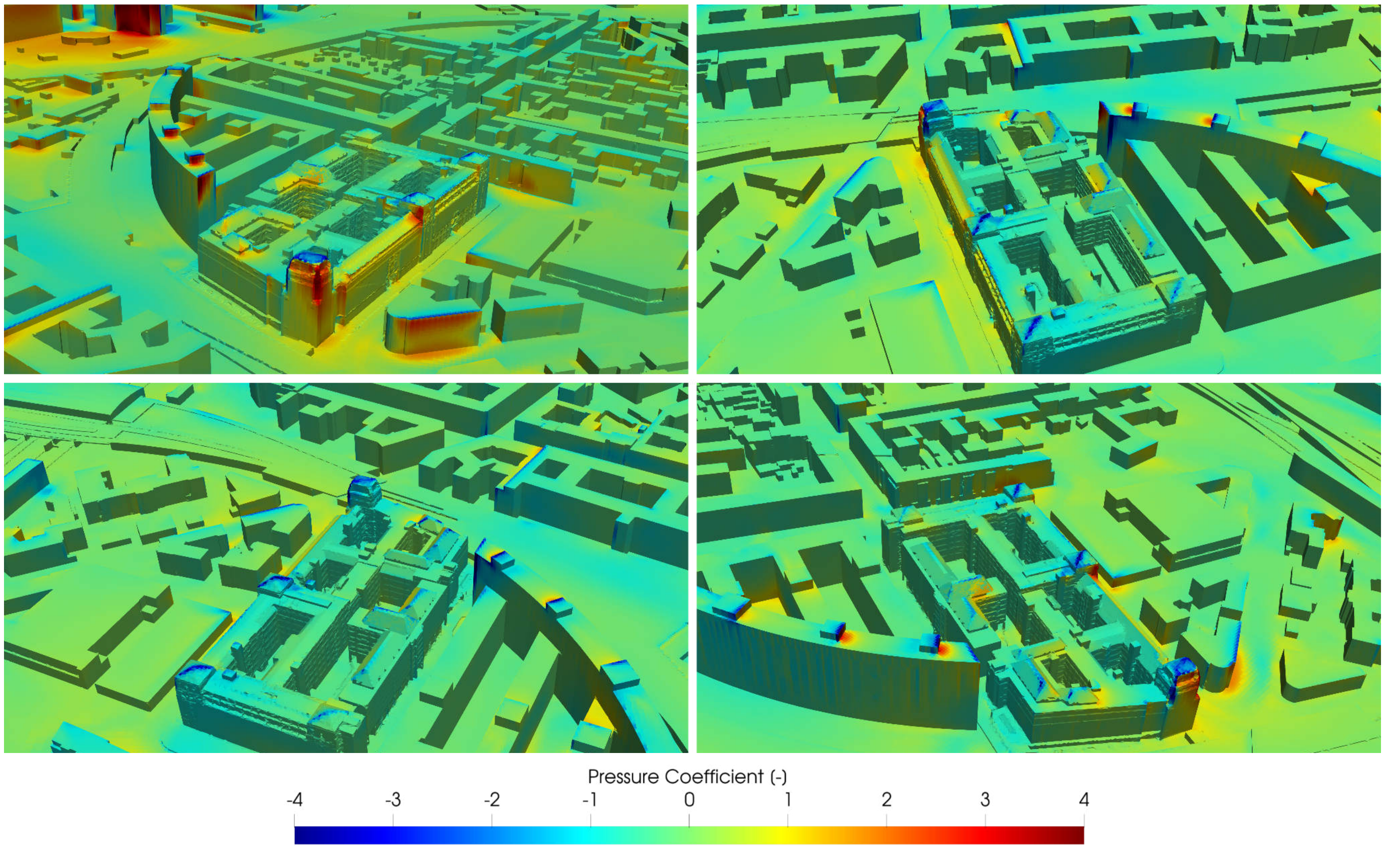


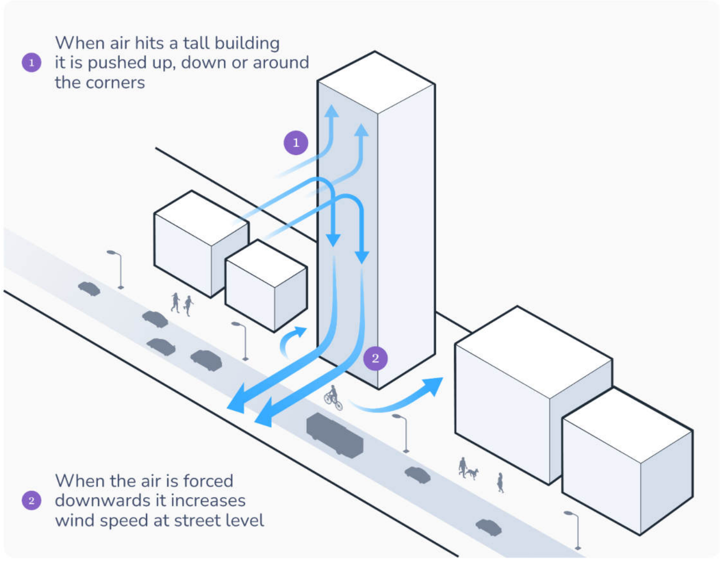
Figure 5.24: Pressure coefficient, wind from 270° (extreme weather conditions)

6. Pedestrian Wind Comfort Assessment

In this chapter, the Pedestrian Wind Comfort Assessment is carried out by using computational wind data from the CFD simulations, meteorological data, and specific comfort standards, namely Lawson and NEN8100. This methodology provides a rigorous and accurate appraisal of wind conditions affecting pedestrians.

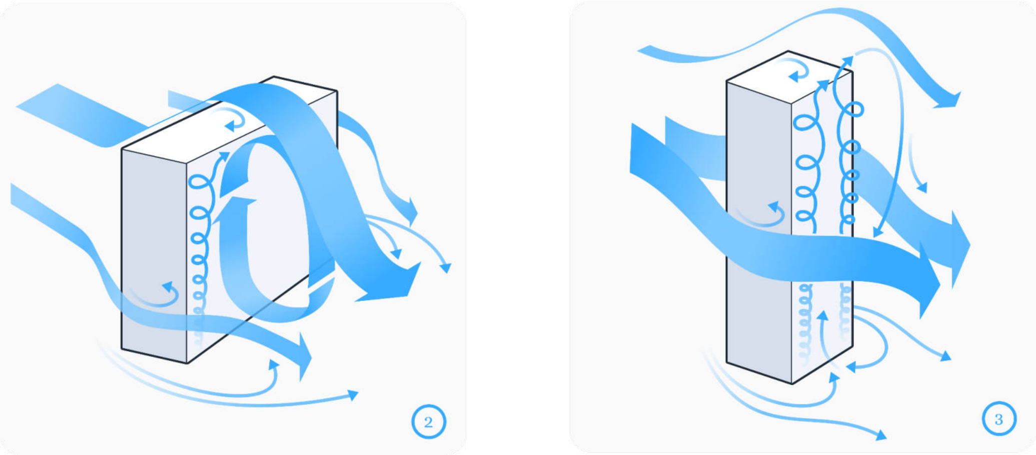
Understanding the importance of this assessment requires a grasp of how air interacts with building structures:

- When air encounters a tall building, it is deflected in various directions: up, down, or around the corners. This diversion substantially influences local wind behavior.
- Air forced downward by the building increases the wind speed at street level. This accelerated wind can significantly affect pedestrian comfort and safety.



The Pedestrian Wind Comfort map serves as a valuable tool for decoding these interactions. It provides insights into zones that are impacted by the building-induced wind modifications. Moreover, it helps identify areas where people can comfortably engage in their specific activities: whether it be walking, sitting, or any other tasks. Therefore, the comfort map becomes instrumental not just for urban planning but also for social dynamics, as it guides design modifications aimed at enhancing human well-being.

6.1. Flow patterns around buildings



Horizontal high-rise building

Vertically long high-rise building

Figure 6.1: Flow patterns around types of buildings

For horizontally elongated high-rise buildings (Figure 6.1, left), the flow pattern tends to exhibit significant separation and recirculation zones along the length of the building. Wind speed is often reduced immediately behind the building due to the wake effect, creating a region of lower velocity. However, at the building corners, accelerated flow, or "corner streams," can be observed, which may lead to heightened wind conditions at pedestrian levels.

In vertically elongated high-rise buildings (Figure 6.1, right), the flow patterns are more dominated by "downwash" effects. The wind flowing over the top of the building creates a downward flow along the building facade. This downwash merges with the approaching wind and can cause higher wind speeds at the base of the building. There's also the likelihood of vortices forming, especially in the leeward region, creating complex and potentially problematic wind conditions at ground level.

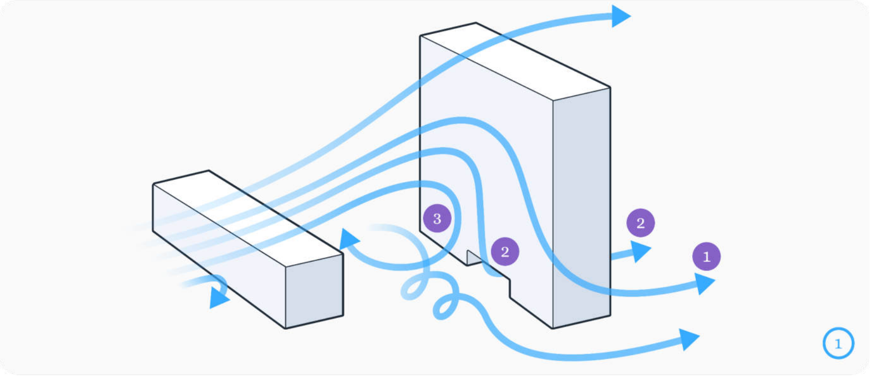
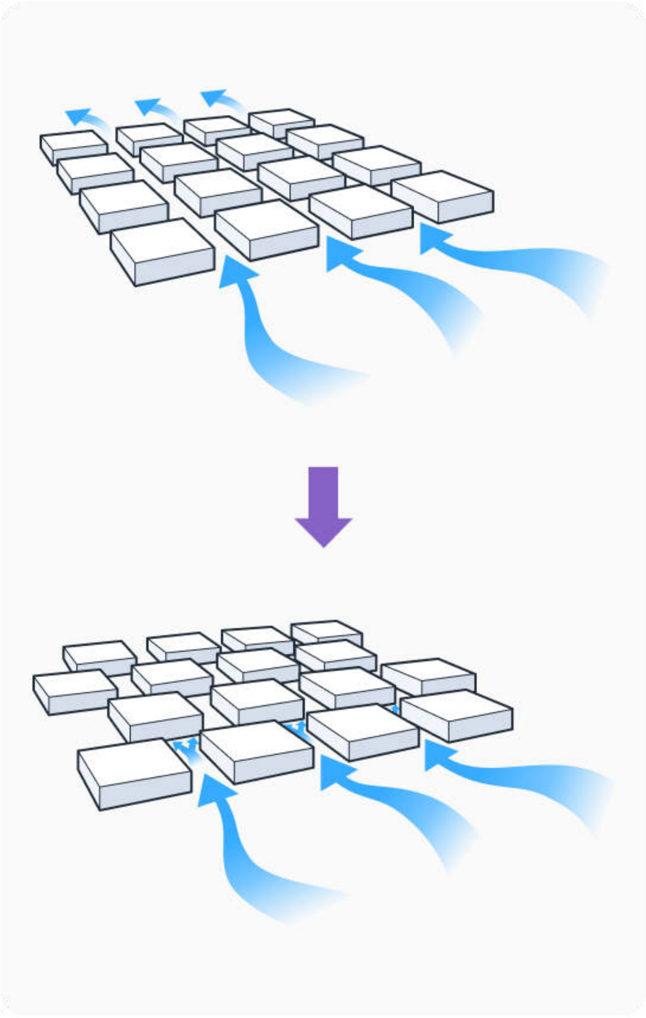


Figure 6.2: Three typical wind patterns that occur around buildings

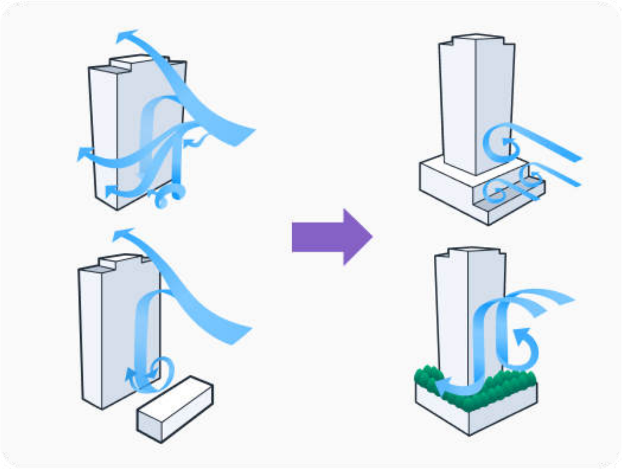
As depicted in Figure 6.2, the aerodynamic interactions around buildings manifest in distinct ways:

1. **Strong Wind at Corners:** The figure illustrates the phenomenon of wind acceleration at the building corners, commonly referred to as "corner streams." This localized increase in wind speed is generally a concern for pedestrian comfort and must be accounted for in wind studies and mitigation measures.
2. **Flow Through Narrow Spaces:** The figure also shows wind channelling between adjacent structures or narrow passages. These areas tend to have increased wind velocities and can lead to uncomfortable or even hazardous conditions.
3. **Reverse Flow Patterns:** Notably, Figure 6.3 highlights instances of reverse flow patterns, particularly in the wake regions behind the buildings. These areas can exhibit recirculating air flows and are generally characterized by lower wind speeds, but can be tricky to manage in terms of air quality and ventilation.

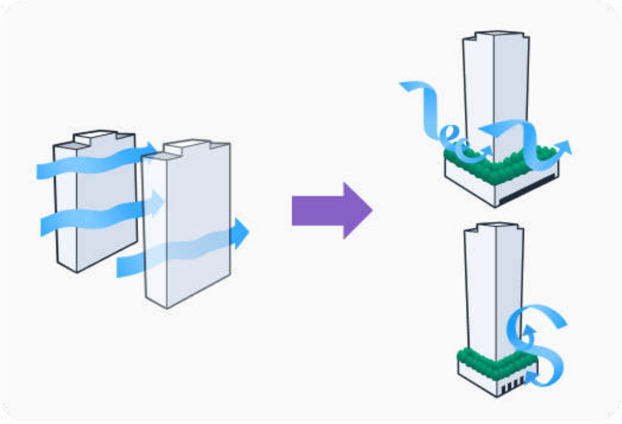
6.2. Mitigation Measures



Narrow and winding streets make airflow slow



Mitigation Measures for Downwash and Downdraft Effects



Mitigation Measures for Funneling Effects

Figure 6.3: Possible mitigation measures to improve pedestrian wind comfort

To enhance pedestrian wind comfort, the following measures, as depicted in Figure 6.3, can be implemented:

- **Building Orientation:** Realign buildings to reduce wind channeling and lower pedestrian-level wind speeds.
- **Building Shape & Design:** Modify shapes and facades to disrupt wind flow and minimize downwash effects.
- **Landscape Elements:** Use trees, hedges, or green walls as natural windbreakers.
- **Wind Barriers:** Install fences or screens to redirect airflow and reduce wind speeds in problem areas.

The presence of trees near the Bremsenwerk complex already serves as an inherent wind mitigation strategy, as shown in Figure 6.4. These trees are positioned where computational fluid dynamics (CFD) simulations highlight elevated wind speeds, effectively functioning as natural windbreakers.

Figure 6.4: Trees serving as wind mitigation measures near the Berliner Bremsenwerk complex

6.3. Comfort Map

6.3.1. Lawson Comfort Criteria

The Lawson Comfort Criteria serve as the framework for evaluating pedestrian wind comfort around the Berliner Bremsenwerk complex. This set of guidelines categorizes wind conditions into activity-specific comfort levels, such as sitting, standing, and strolling. Figure 6.5 presents a comfort map based on the Lawson Criteria, providing both a visual and quantifiable assessment of wind conditions in the area. This map is pivotal for understanding the impact of the local microclimate on pedestrian-level wind comfort and informs any necessary mitigation strategies.

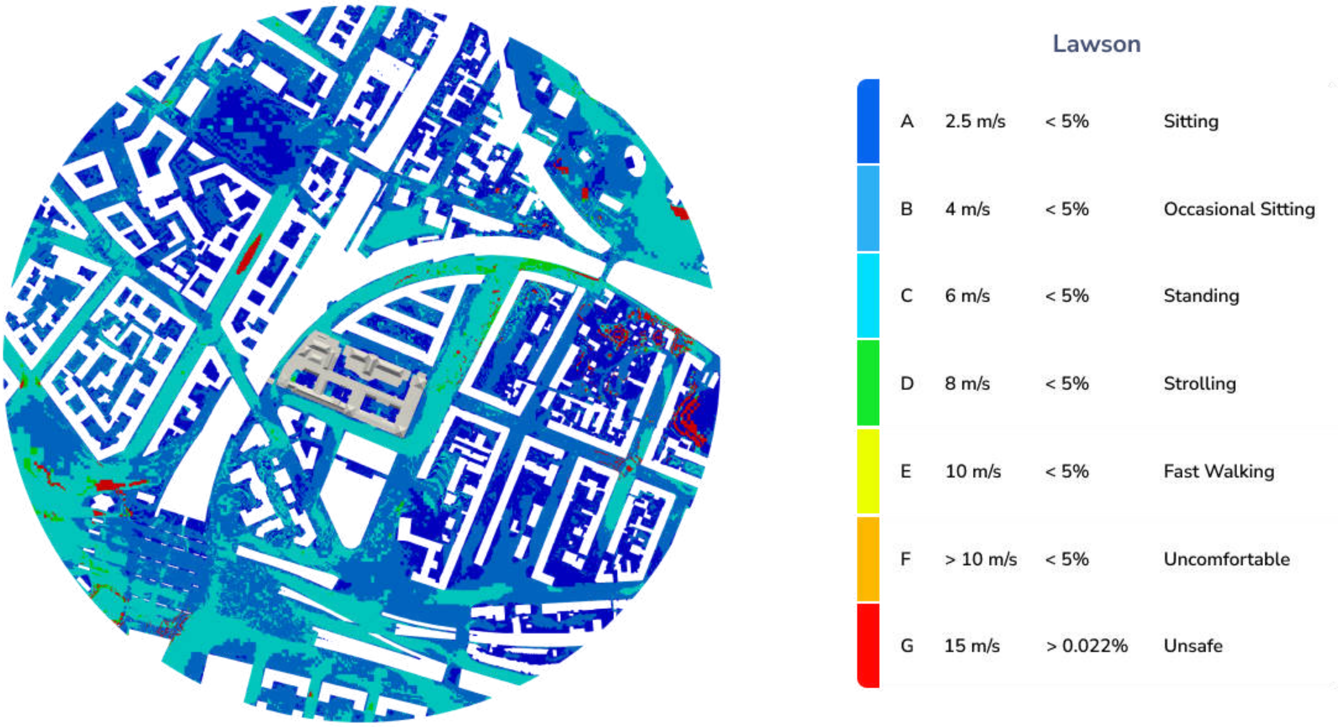


Figure 6.5: Pedestrian Comfort Map based on the Lawson comfort criteria

It can be observed that:

- The majority of areas around the building are well-suited for both sitting and standing activities.
- The southwestern and southern sections of the building offer potential for comfort optimization through strategic tree planting, which can serve as windbreakers.
- Overall, the Bremsenwerk complex poses no challenges regarding pedestrian wind comfort.

6.3.2. NEN8100 Comfort Criteria

An alternative way to analyze pedestrian wind comfort is through the NEN8100 comfort criteria from the Dutch Norm. Unlike the Lawson criteria, NEN8100 focuses on a 5m/s wind speed threshold. This standard offers another method for evaluating wind conditions around the Bremsenwerk complex, as shown in Figure 6.6.

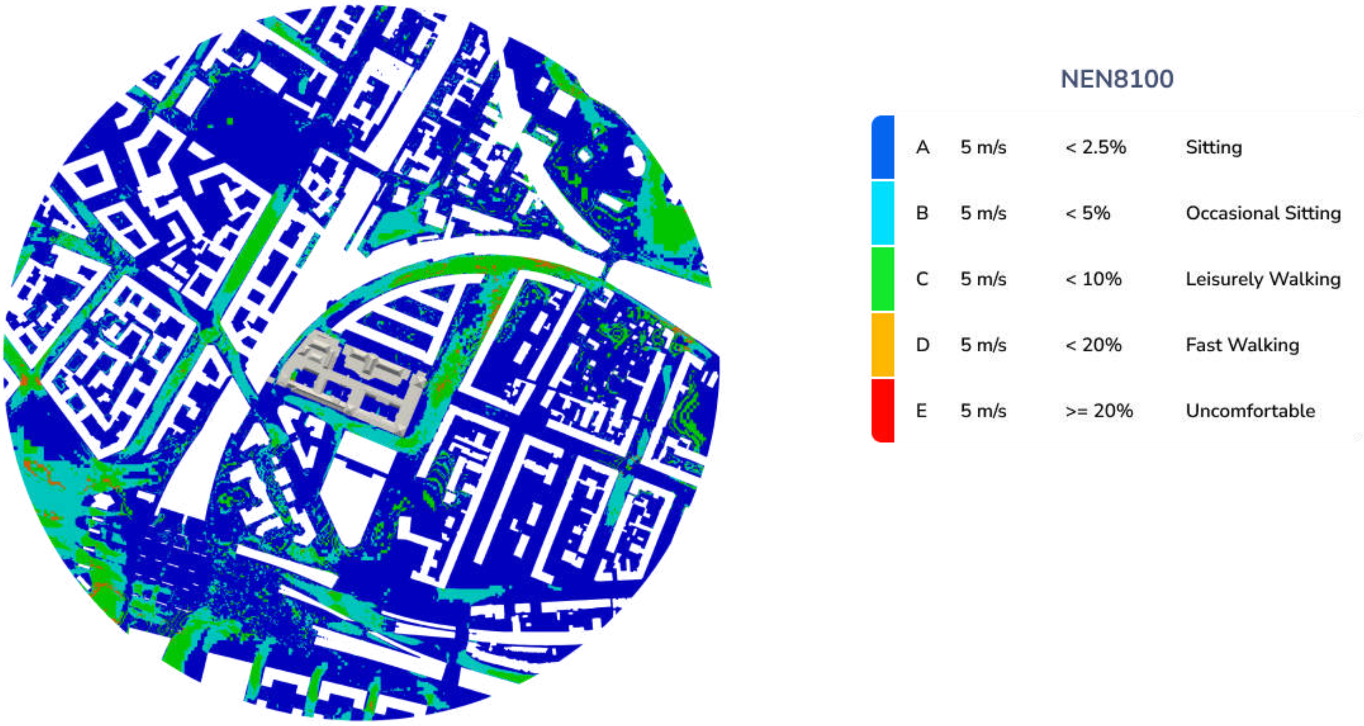


Figure 6.6: Pedestrian Comfort Map based on the NEN 8100 comfort criteria

Results align closely with those based on the Lawson criteria and offer clearer insights, particularly for areas suitable for walking. Similar to the Lawson criteria, the NEN8100 standard reveals that no mitigation measures are necessary. It also identifies the southwestern and southern sections of the building as areas for potential comfort optimization through strategic tree planting, which can serve as windbreakers.

7. Climate Change Impact

The European Commission's 2020 report "Impacts of climate change on windstorms" indicates that wind speeds are largely expected to remain stable across most of Europe under a 3°C warming scenario. Specifically, wind extremes are anticipated to increase only in Southern Europe, covering 17% of that region's land area. Since Berlin is situated in Central Europe, it does not fall within the area expected to experience significant changes in wind speeds. The report also notes a robust tendency toward more calm days (defined as days with maximum wind speeds below 3.5 m/s) particularly in central, western, and eastern Europe. Therefore, based on this source, no significant changes in wind speeds or extremes are anticipated for Berlin.

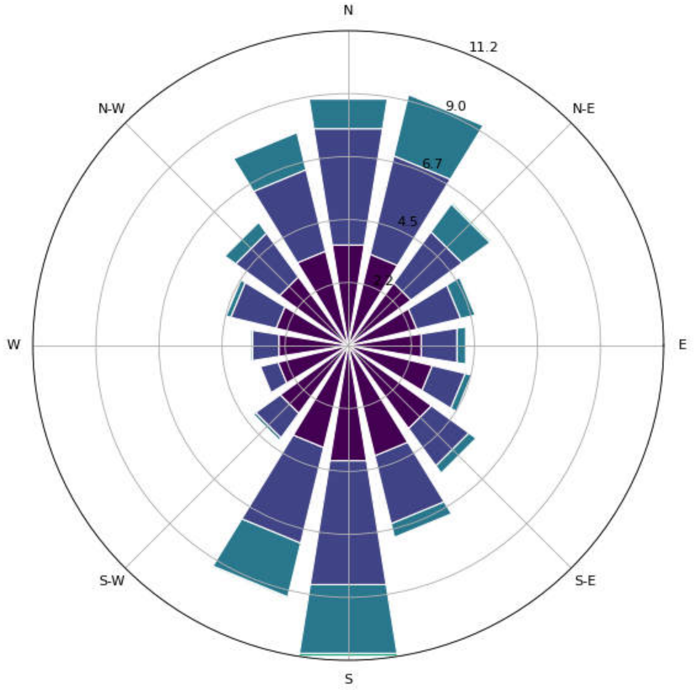


Figure 7.1: Wind Rose Projection for 2100 Based on High-Emissions Scenario RCP8.5, Utilizing CMIP6 Global Climate Models

Data projections under high emissions (RCP8.5) and moderate mitigation scenarios (RCP4.5) were utilized to estimate changes in wind hazard for Berlin for global warming levels of 1.5, 2, and 3°C above preindustrial levels. Using wind damage functions that relate construction stock, wind speed, and economic losses, as well as reported fatalities from past events, a wind rose for Berlin was generated. The results align with the prevailing assessment that no significant change in wind conditions is expected for the area.

In light of these findings, a specialized pedestrian wind comfort assessment for future conditions in Berlin is not required. The wind rose generated based on current data from the local weather station provides an already accurate representation of conditions, validating the assessment that no significant changes in wind conditions are anticipated.

8. Key Findings

This report presents a comprehensive microclimate study around the Bremsenwerk building. The objectives were twofold: to examine the building's impact on pedestrian wind comfort under typical wind conditions in Berlin and to assess the building's structural resilience to specific extreme wind events.

Preliminary results of the wind microclimate study for the Berliner Bremsenwerk complex reveal:

- Dominant winds predominantly emanate from the west to southwest, with an average speed of about 4 m/s.

- According to both Lawson and NEN8100 criteria, no mitigation measures are strictly necessary. However, pedestrian comfort could be enhanced by introducing additional landscaping or trees on the building's western to southwestern side.

- Elevated pressure levels have been observed on the building's northwestern tower, potentially posing a risk of structural damage, particularly during extreme weather conditions.

9. Future Work

For future studies to enhance the robustness and accuracy of the microclimate analysis around the Berliner Bremsenwerk complex, the following recommendations can be made:

- **More Accurate Grid:** Implement a finer mesh grid to capture subtler fluid dynamics phenomena, thus improving simulation accuracy.

- **Transient and Highly-Detailed Simulation:** Consider conducting transient simulations to capture time-dependent wind behavior, employing higher-fidelity turbulence models for greater detail. Additionally, assess structural fatigue due to cycles of wind loading for long-term resilience.

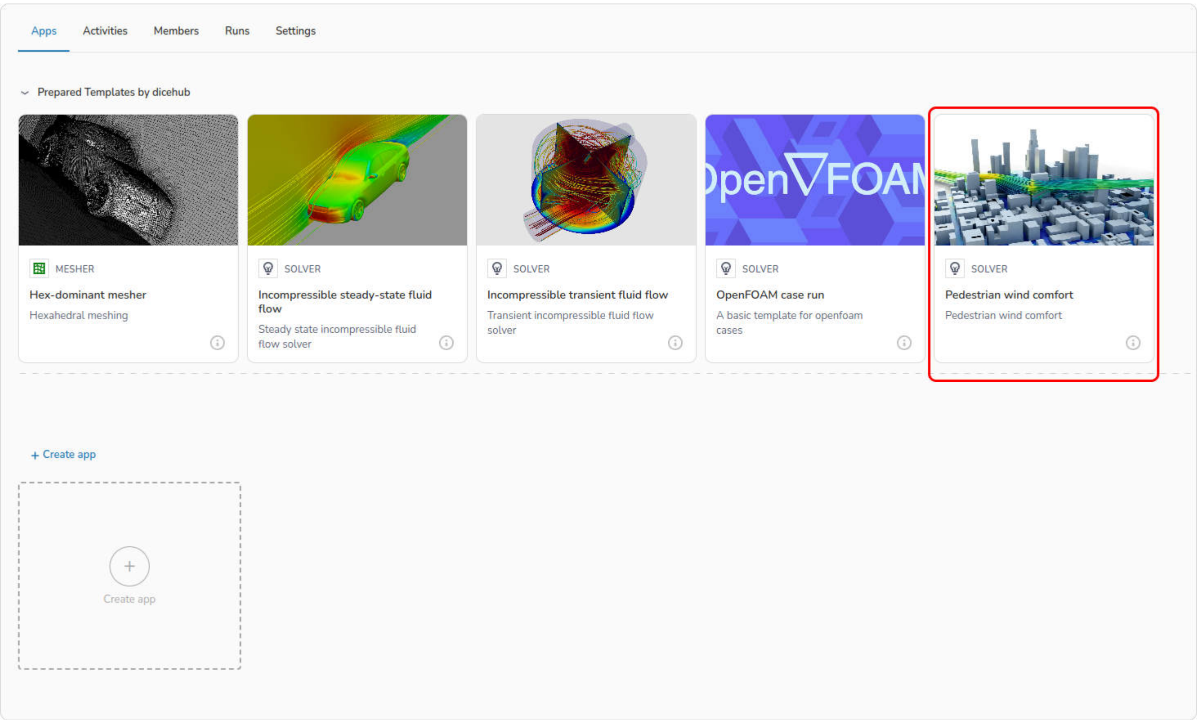
- **Adaptive Simulations:** Re-run simulations to account for additional design modifications, such as new landscaping features modeled as porous zones, or other mitigation measures that may be deployed.

- **Increased Directional Detail:** Expand the number of wind directions analyzed from the current 16 to between 32 and 36 to comprehensively evaluate wind behavior around the building from all angles.

Appendix

Simulation procedure in dicehub

1. Create application



Prepared Templates by dicehub

MESHER
Hex-dominant mesher
Hexahedral meshing

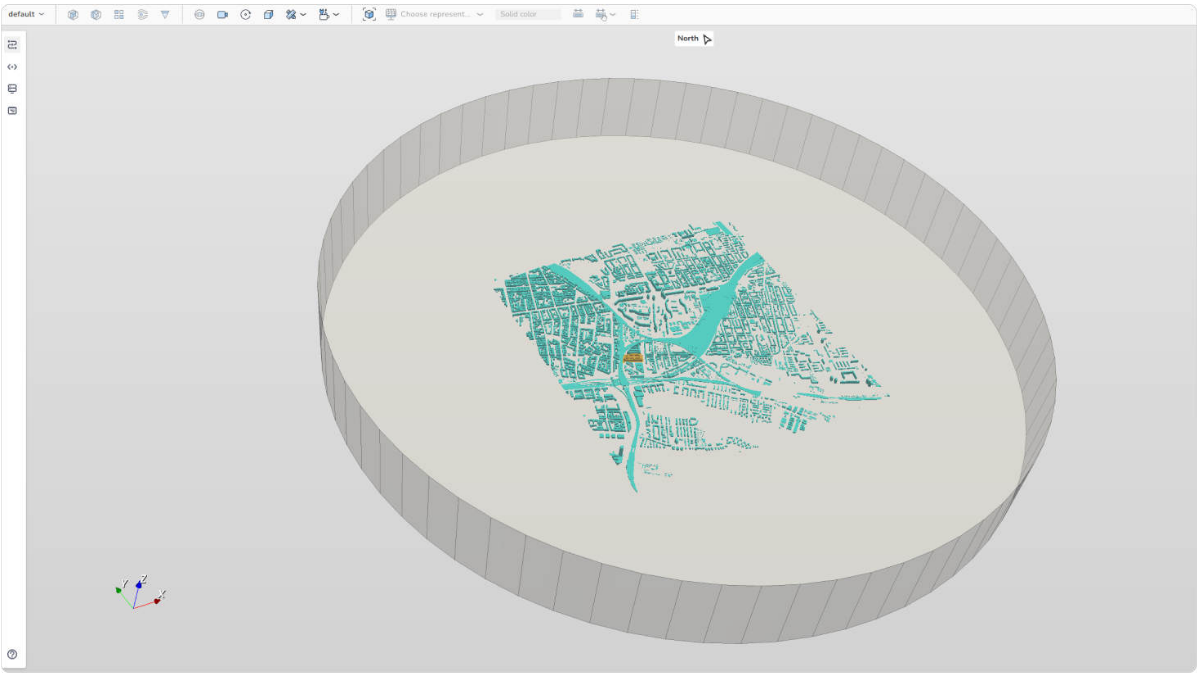
SOLVER
Incompressible steady-state fluid flow
Steady state incompressible fluid flow solver

SOLVER
Incompressible transient fluid flow
Transient incompressible fluid flow solver

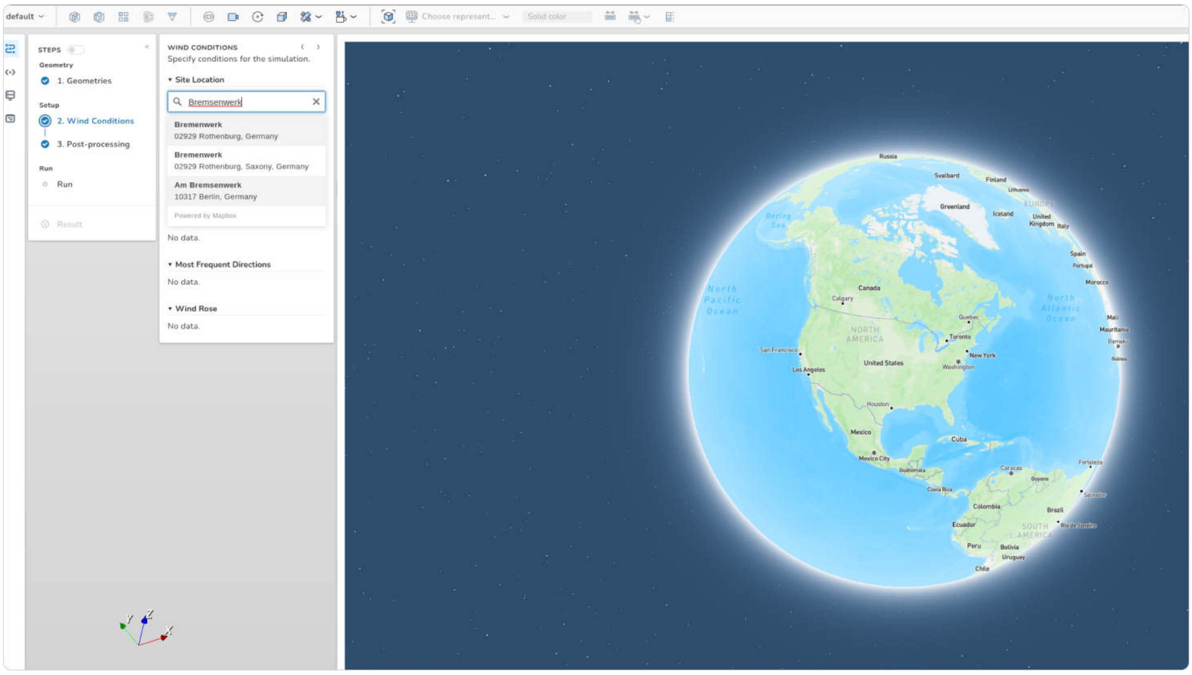
SOLVER
OpenFOAM case run
A basic template for openfoam cases

SOLVER
Pedestrian wind comfort
Pedestrian wind comfort

2. Import Geometry



3. Select site location



WIND CONDITIONS
Specify conditions for the simulation.

▾ Site Location

Bremsenwerk

Bremenwerk
02929 Rothenburg, Germany

Bremenwerk
02929 Rothenburg, Saxony, Germany

Am Bremsenwerk
10317 Berlin, Germany

Powered by Mapbox

No data.

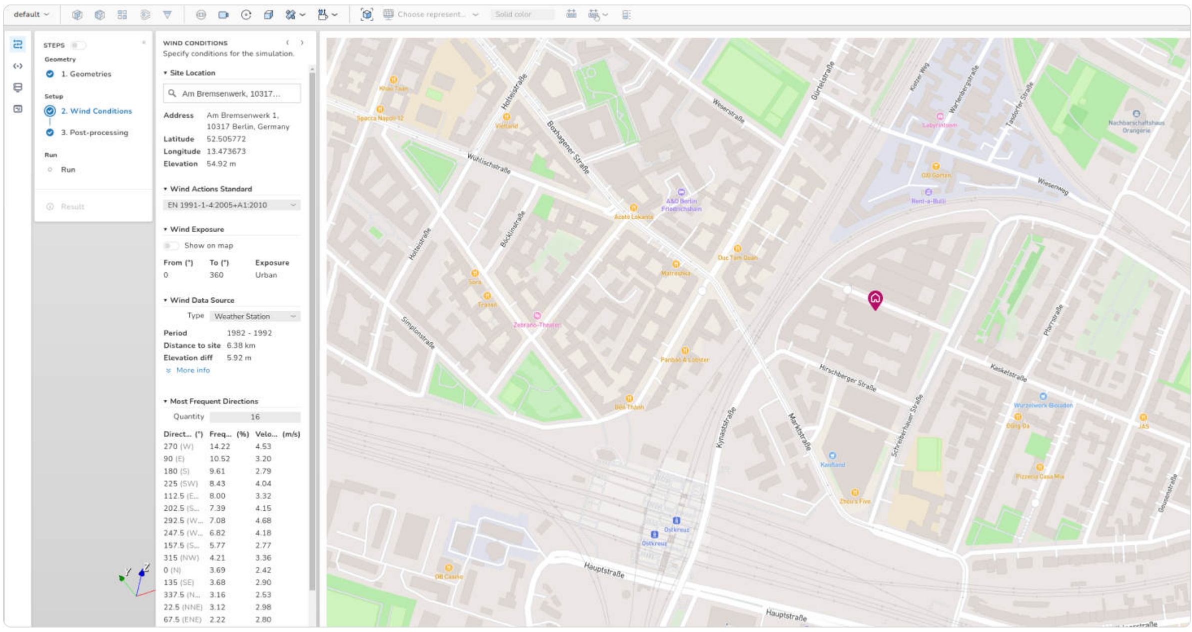
▾ Most Frequent Directions

No data.

▾ Wind Rose

No data.

4. Select amount of wind directions for the study



WIND CONDITIONS
Specify conditions for the simulation.

▾ Site Location

Am Bremsenwerk, 10317...

Address Am Bremsenwerk 1,
10317 Berlin, Germany
Latitude 52.505772
Longitude 13.473673
Elevation 54.92 m

▾ Wind Actions Standard

EN 1991-1-4:2005+A1:2010

▾ Wind Exposure

Show on map

From (°)	To (°)	Exposure
0	360	Urban

▾ Wind Data Source

Type Weather Station

Period 1982 - 1992
Distance to site 6.38 km
Elevation diff 5.92 m
More info

▾ Most Frequent Directions

Quantity 16

Direct... (°)	Freq... (%)	Velo... (m/s)
270 (W)	14.22	4.53
90 (E)	10.52	3.20
180 (S)	9.61	2.79
225 (SW)	8.43	4.04
112.5 (E...	8.00	3.32
202.5 (S...	7.39	4.15
292.5 (W...	7.08	4.68
247.5 (W...	6.82	4.18
157.5 (S...	5.77	2.77
315 (NW)	4.21	3.36
0 (N)	3.69	2.42
135 (SE)	3.68	2.90
337.5 (N...	3.16	2.53
22.5 (NNE)	3.12	2.98
67.5 (ENE)	2.22	2.80

5. Run and evaluate results

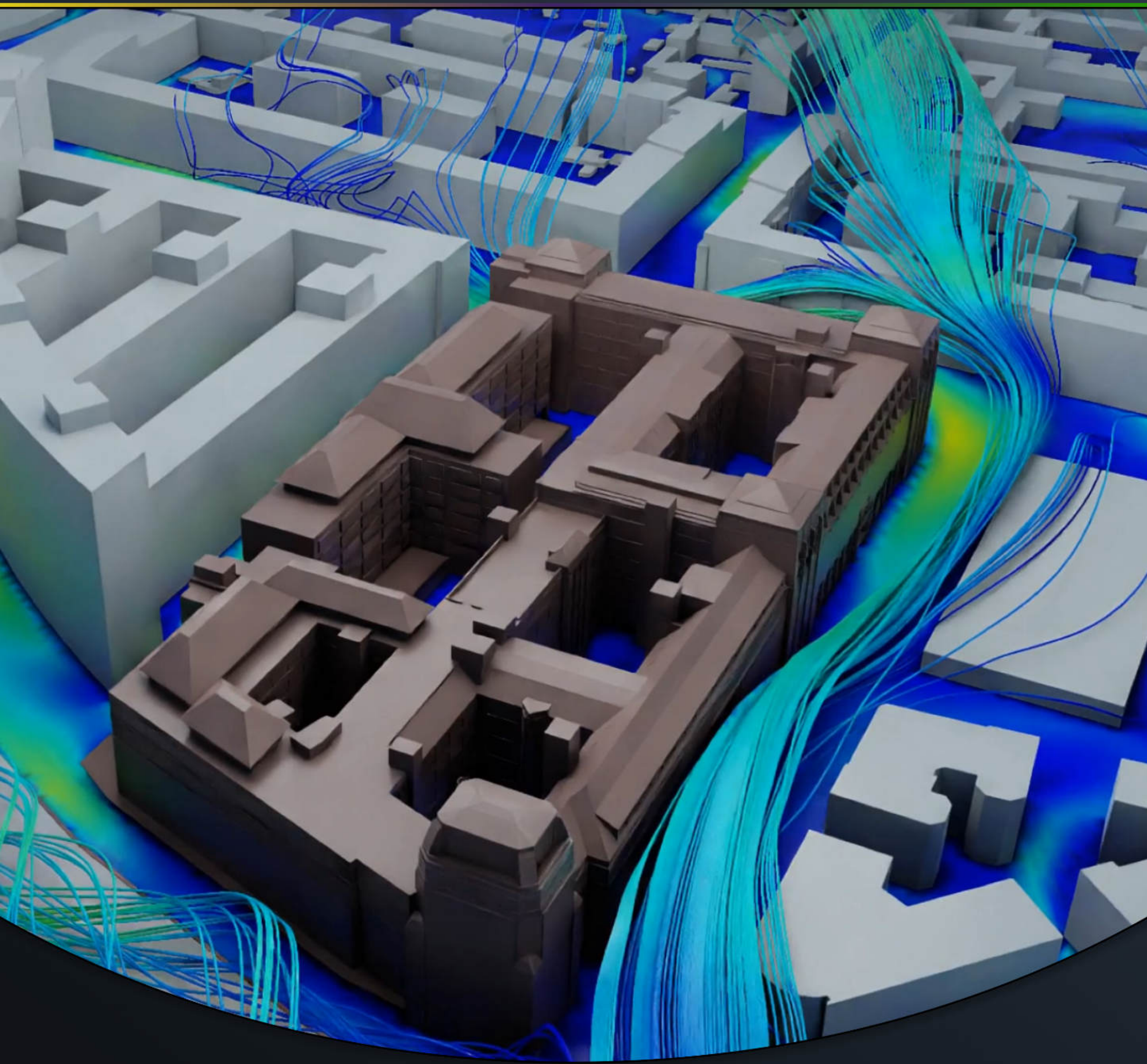
References

[1] Architectural Institute of Japan. (2020). Guidebook for CFD Predictions of Urban Wind Environment.

[2] Franke, J., Hellsten, A., Schlünzen, H., and Carissimo, B. (2007). Cost Action 732-best Practice Guideline for the CFD Simulation of Flows in the Urban Environment. Brussels, COST: Cambridge Environmental Research Consultants.

[3] Franke, J., Mochida, A., Tominaga, Y., and Yoshie, R. (2006). "TA4 CFD Guideline for Pedestrain Wind Environment (Organized Session), Wind Engineers, JAWE," in 2006 The fourth international symposium on computational wind engineering (Yokohama: JapanCiteseer), 529–536. doi:10.5359/jawe.2006.529

[4] Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., et al. (2008). Aij Guidelines for Practical Applications of CFD to Pedestrian Wind Environment Around Buildings. J. Wind Eng. Industrial Aerodynamics 96, 1749–1761. doi:10.1016/j.jweia.2008.02.058



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