Wind Driven Design

A starting point towards a wind-oriented design approach

Graduation: Architectural Engineering

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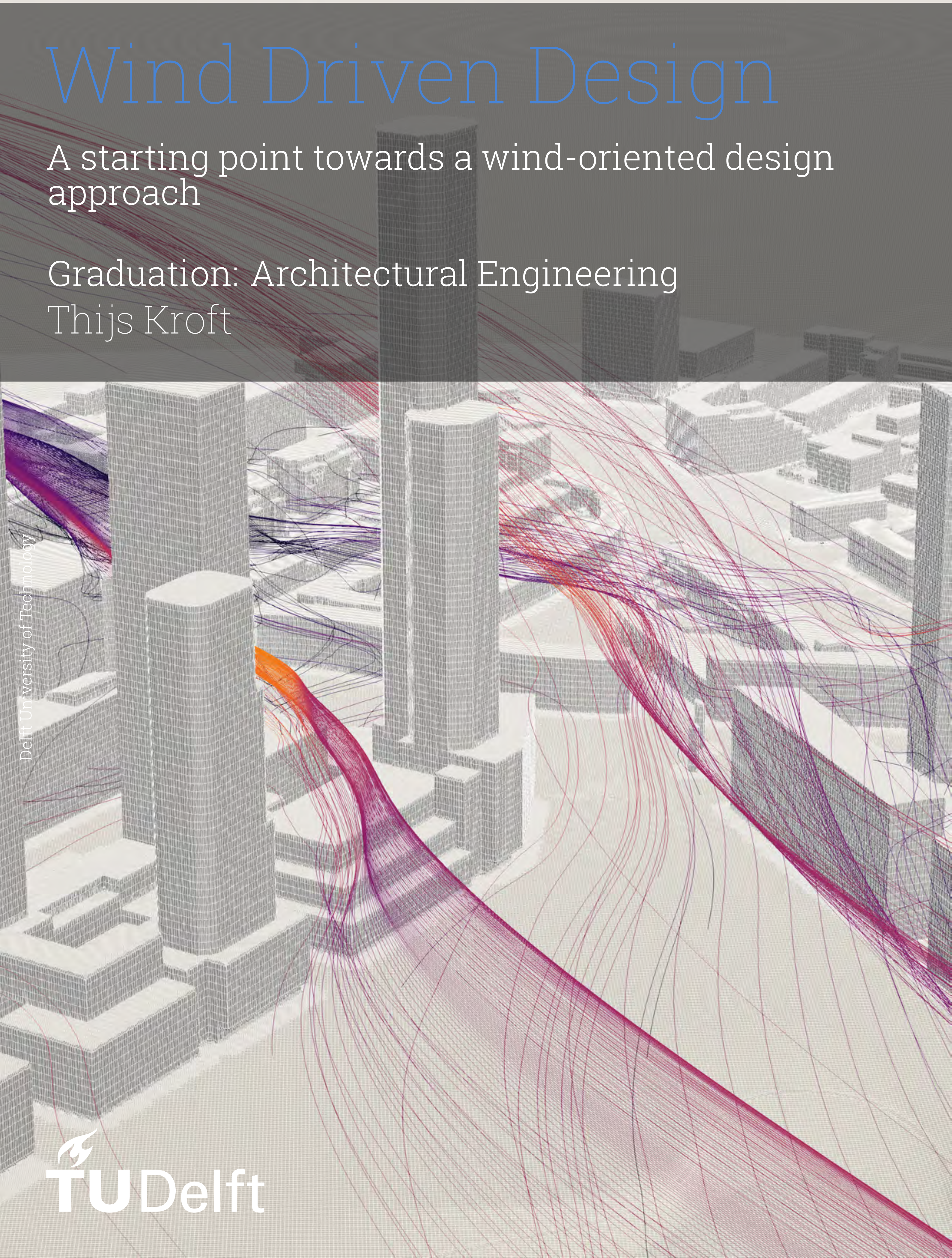

Wind Driven Design

A starting point towards a wind-oriented design approach

by

Thijs Kroft

to obtain the degree of Master of Science
at the Delft University of Technology,

faculty of Architecture and the Built Environment
Architectural Engineering

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Preface

Before you lies the master thesis "Wind Driven Design: A Starting Point Towards a Wind-Oriented Design Approach," written to fulfill the requirements for a Master's degree in Architecture at the Faculty of Architecture and the Built Environment.

Throughout my education, I observed that many designers rely heavily on intuition during the design process. While this approach can often leads to great results, I always struggled with this approach as I wanted to know exactly why something worked. This thesis offered me the opportunity to dive deep into a subject that i was not yet familiar with, learning as much as possible, and finding out how this deep understanding would impact the design process, and if it is even worth it to dive this deep into a subject as an architectural designer.

My interest in wind began during a conversation with my roommate Tim, who explained how car shapes affect fuel consumption. This sparked the question: if the shape of buildings influences wind patterns, could this impact be harnessed positively? During this project, I discovered the significance of wind in architecture and how knowledge of wind behavior can help use reduce dangerous situations as well as improve the ventilation capacity of our cities.

I would like to thank my research mentor, Clara, for her invaluable guidance and support, as well as my design mentor Mauro for keeping me on track architecturally. Thirdly, many thanks to Hans Hoogenboom and the VR-Lab, for the use of the equipment that was required for this research. Furthermore, I want to thank the employees at Actiflow, for sharing their experience and perspective. Finally, Simone Tax. Your master thesis formed the starting point for this project, and it would not be the same without your valuable insights.

Thijs Kroft
Delft, July 2025

Abstract

Using Computational Fluid Dynamics (CFD) simulations, a series of design strategies were evaluated for their impact on local wind conditions in Rijnhaven, Rotterdam, a site facing both ambitious urban development and strict wind regulations. The study identifies how design interventions such as aerodynamic shaping, podiums, and open floors can significantly reduce wind discomfort at street level, particularly on the leeward side of buildings. The result is a workflow aimed at guiding architects in designing with wind more intuitively and effectively.

This research demonstrates that incorporating wind analysis early in the design process can not only improve environmental conditions but also support more coherent and informed architectural outcomes.*Wind behavior is complex and not intuitive. Despite its significant impact on urban environments, the topic remains underexplored in architectural design practice. Meanwhile, as cities continue to densify and buildings rise to increasing heights, designing with wind comfort in mind becomes increasingly more important. This thesis explores how wind behavior can be effectively integrated into early-stage high-rise design to improve outdoor comfort and safety.*

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This research demonstrates that incorporating wind analysis early in the design process can not only improve environmental conditions but also support more coherent and informed architectural outcomes.

Key Words

Wind, Computational Fluid Dynamics (CFD), Outdoor Climate, Building Physics, High-Rise Design

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Introduction

1.1. Problem Statement

The evolution of high-rise buildings in the Netherlands began in the late 20th century as urban centers sought to accommodate population growth and economic development within limited space. Initially concentrated in cities such as Rotterdam and The Hague, high-rise construction has since become a prominent feature of many Dutch urban landscapes. While these developments have contributed to urban densification and skyline transformations, they have also introduced new challenges related to urban comfort. One of the key concerns is the impact of high-rise structures on local wind conditions.

High-rise buildings can significantly alter local wind patterns, resulting in unsafe wind conditions for pedestrians and cyclists. This issue is particularly relevant in Dutch cities, where strong prevailing winds are common, and public spaces are extensively used for various urban activities. Despite the rapidly advancing field of aerodynamics, urban designers as well as architects still have a very limited understanding of the impact their designs have on local wind patterns. This lack of understanding, combined with regulations that require wind-tunnel testing or CFD simulations, frequently results in less than ideal last-minute efforts to mitigate wind dangers. These last-minute efforts are often not very effective at mitigating the problem nor very visually appealing.

Even when architects want to circumvent wind-related problems around their designs, they find themselves attempting to navigate through a heavy swamp of highly technical research that requires years of training to even understand the gist. Architects are trained to design, not to understand math.

Now that buildings are rising to ever increasing heights, understanding wind in an urban environment is more crucial than ever. If we do not take wind into account with these new high-rises, we are stuck with a terrible wind environment for a long time. Therefore, we must take action now and make sure that architects and urban designers take this topic into account while designing. A short and understandable workflow relating to wind for architects and urban designers is missing. This thesis will be a starting point towards a more widespread understanding of wind behavior in the architectural profession.

1.2. Objective

The goal of this project is to assist architectural designers in incorporating wind into the earlier stages of their design. In practice, architectural designers often do not understand the impact of their buildings on the local wind climate. Often, this leads to undesirable outcomes. The outcome of this research is a workflow that can help architectural designers prevent these undesirable outcome.

1.3. Research question and thesis outline

Due to the complexity the task at hand, the scope of this research will be limited to a specific location; Rijnhaven in Rotterdam. The urban plan for this location has recently been finalized and includes *requirements for wind speeds in the surrounding area. These requirements are challenging to meet, due to the unique situation of high-rise buildings situated next to the water front. This research paper aims to provide a workflow for architects to help incorporate wind behavior into their early design concepts and therefore create a better and more integrated design. This results into the following research question:*

How can an improved understanding of wind behavior be integrated into high-rise design strategies to enhance pedestrian comfort and safety in Rijnhaven, Rotterdam?

The resulting workflow provides a practical guide for architectural designers in Rijnhaven who aim to incorporate wind considerations into their designs. It will feature several design strategies to enhance local wind conditions around their structures, along with methods for testing these strategies' effectiveness. The master plan for Rijnhaven is notably ambitious, envisioning multiple multifunctional towers reaching around 200 meters in height, complemented by extensive new greenery. Social aspirations for the area are equally high; the development aims to create a vibrant urban center that serves as a meeting place for residents from nearby neighborhoods Kop van Zuid, Katendrecht, and the Afrikaanderwijk—each with its distinct identity and character. Integrating these diverse ambitions with the wind-driven design approach brings us to the following design question:

How does the incorporation of a wind-based design workflow impact the design process of a multifunctional high-rise building in the the urban context of Rijnhaven, Rotterdam?

1.4. Success

*The workflow can be seen as successful when it leads to a design that leads to a comfortable wind climate as well as sufficient freedom in the design process. For the determination of what a "comfortable" wind climate is, the (*NEN8100 *2006) will be used. This norm sees different wind conditions as comfortable for different activities. The workflow should help architects deal with wind comfort while improving on design quality.*

2

Methodology

2.1. Introduction

This chapter includes the method in which the research and design questions will be answered. It includes the expected outcomes as well as the intended means to that end. This research primarily makes use of the theoretical framework as proposed in (BLocken, Janssen, and Hooff 2011). This paper includes best practice guidelines that are relevant for this research project.

2.2. Hypothesis

In the introduction, the following research question is established: How can an improved understanding of wind behavior be integrated into high-rise design strategies to enhance pedestrian comfort and safety in Rijnhaven, Rotterdam?

as well as the following design question: How does the incorporation of a wind-based design workflow impact the design process of a multifunctional high-rise building in the the urban context of Rijnhaven, Rotterdam?

It is expected, that by incorporating a wind-oriented workflow in the earlier stages of the design process for high-rise buildings, the pedestrian comfort at street level will increase by creating a more favorable wind climate. Furthermore, by taking wind into account at an earlier stage, the final design will be more in line with the original architectural vision.

2.3. Theoretical Background

In this chapter, the theoretical aspects of this research are studied and explained. Through a literature review, this chapter starts with an explanation on what is seen as a good wind climate. The second part of this chapter relates to the behavior of wind, closing of with design strategies that can be used to improve the wind climate.

2.4. Workflow Development

In this chapter, several design strategies will be tested. For this, due to the lack of availability of a wind tunnel, as well as the abundant availability of computing power for this research, CFD simulations are chosen as the main method to predict wind behavior on the chosen cite.

2.4.1. Software

This specific research is caried out in OpenFOAM (OpenFOAM Foundation 2024). This particular piece of software is chosen as it is open sourced, offers a lot of flexibility but primarily because the research mentor for this project is familiar with it. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is used to iteratively solve the continuity and momentum equations. simpleFoam is a pressure-based solver for steady-state simulations of incompressible flow. The simula-

tions make use of a k-epsilon turbulence model as well as RANS (Reynolds-Averaged Navier Stokes) (Greenshields and Weller 2022) (Gorlé, García-Sánchez, and Iaccarino 2015) (Longo et al. 2017).

2.4.2. Reliability

In order to make trustworthy claims about results of CFD simulations, several steps need to be taken in order to show that a simulation is accurate enough. While the governing equations are proven to be correct and are the same for all RANS simulations, there are elements that are different for most simulations. These elements are user input and are therefore open to error (Terry 2018).

Residuals

Residuals in CFD are used to determine how accurately the governing equations behind the computational model have been solved. For this study, typical residuals can be seen in figure 2.1

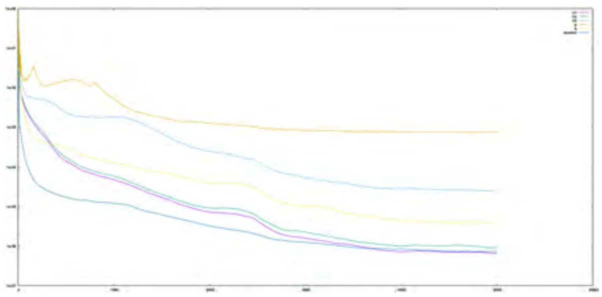


Figure 2.1: Resulting residuals for one of the completed simulations

Grid Convergence

One element that needs to be proven to be correct is the refinement of the simulated mesh. This is referred to as grid convergence. In this thesis, this is done in accordance to the method that is proposed by (Celik et al. 2008) and (Roache 1994). In these papers, The grid convergence index is calculated for 3 scenarios. A course mesh, a fine mesh and a finer mesh. In this thesis, the course mesh has 45 million cells, the fine mesh has 64 million cells and the finer mesh has 83 million cells. After consideration with the research mentor of this project, it was decided to continue with the fine mesh.

(a) Course mesh

(b) Fine mesh

(c) Finer mesh

Figure 2.2: Grid Convergence tests

2.4.3. Site

The geometry of the cite is provided by several different sources. The base buildings, terrain, greenery and water is provided by City4CFD ((Pađen, García-Sánchez, and Ledoux 2022) and (Pađen, Peters, et al. 2024)) which is a tool that helps construct terrain based on 3DBag data as well as pointcloud data. Missing geometry is acquired from Actiflow and the municipality of Rotterdam.

2.4.4. Wind Statistics

The wind climate is different for every place in the world. This means that, in order to predict the conditions in a certain location, we need to measure the wind speeds in that location. The (NEN8100 *2006) specifies that we must measure at least 12 wind directions, over a period of 40 years. Sadly, measurements are not available for every location in the Netherlands. The NPR itself interpolates data from several measurement stations to get results for a specific locations.*

Due to lack of access to the NPR tool, wind data was acquired from several KNMI measurement stations that are located close to the site of Rijnhaven (KNMI 2025). These locations include Hoek Van Holland, Rotterdam Airport, Rotterdam Geulhaven and Voorschoten. The resulting wind rose can be seen in figure 2.3.

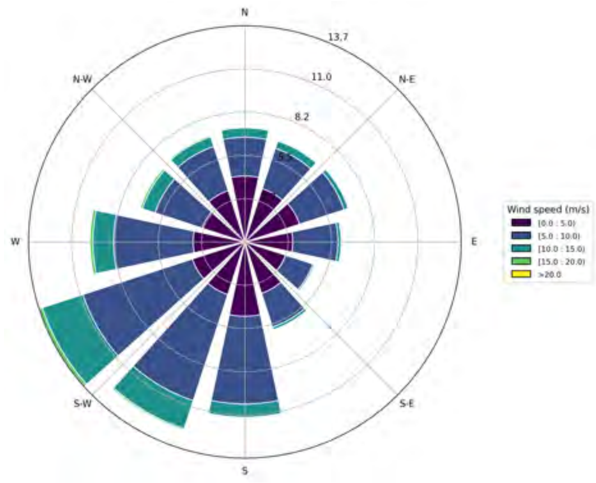


Figure 2.3: Wind Data as used for this research, based on data from

2.5. Success

*The workflow can be seen as successful when it leads to a design that leads to a comfortable wind climate as well as sufficient freedom in the designprocess. For determining what a 'comfortable' wind climate is, the (*NEN8100 *2006) will be used. The NEN 8100 sees different wind conditions as comfortable for different activities. The workflow should help architects deal with wind comfort while improving design quality.*

3

Theoretical Background

3.1. Introduction

In this chapter, the theoretical part of this research is explained. It starts with an explanation of wind comfort and how it is defined, followed by an explanation of wind behavior and its physics. Furthermore, it explains how wind flows can be predicted and how a designer can influence them.

3.2. Wind Comfort

For most of us, wind comfort is a very intuitive thing. Whether or not we find wind comfortable or annoying depends highly on the individual, the temperature, or the activity in which one participates. While quantifying wind comfort is challenging, it is still worth the effort as the effects are serious. (Wise 1970) reports that shops were left untenanted because the windy environment discouraged shoppers. Other authors (Lawson and Penwarden 1975) report on the death of two old ladies due to an unfortunate fall caused by high wind speed at the base of a tall building. Driven by their own examples, many Dutch cities have regulations that direct architects and urban designers towards predefined wind climates.

3.2.1. Regulation

*In the Netherlands, the (*NEN8100 *2006;* NPR 6097:2006 *2006) norms are primarily used to define the characteristics of a comfortable wind climate. This norm defines wind comfort using the probability of accedence for 5 m/s. Requirements are different for different activities.*

Exceedance Probability	**Quality requirements**	**Activities**		
Exceedance of 5 m/s as a percentage of hours per year	class	I. Walking	II. Strolling	III. Sitting for extended periods
< 2.5%	A	Good	Good	Good
2.5 – 5%	B	Good	Good	Moderate
5 – 10%	C	Good	Moderate	Poor
10 – 20%	D	Moderate	Poor	Poor
> 20%	E	Poor	Poor	Poor

Table 3.1: Requirements for assessing the local wind climate for wind nuisance. Based on (*NEN8100* 2006)

*It is important to note that, as of 2024, the (*NEN8100 *2006) is being revised. For this, there are several reasons. The Norm has the exact quality requirements for the entire country, while different cities often have different requirements. Some cities might want to increase wind speeds to reduce urban heat island effects and reduce air pollution, while others might want to decrease wind speeds to reduce dangerous situations. Furthermore, the NEN does not distinguish between summer and winter, while wind statistics fundamentally alter between seasons.*

3.2.2. Wind Danger

*Apart from comfort, the (*NEN8100 *2006) defines wind danger. In a similar method to wind comfort, wind danger is described as a change exceeding 15 m/s. At this wind speed, wind becomes dangerous for healthy adults. The norm calls for separate, more strict rules for places where vulnerable people, such as the elderly, might come often.*

Exceedance Probability	Qualification
$p(v_{LOK} > v_{DR,G})$ *as a percentage of hours per year*	
$0.05 < p < 0.30$	Limited Risk
$p \geq 0.30$	Dangerous

Table 3.2: Requirements for assessing the local wind climate for wind danger. Based on (*NEN8100* 2006)

3.3. Wind behavior

When Architects ask engineers about the bahavior of wind, they can expect a long story filled with math and difficult concepts. While all of this is important, the architect does not need to know the entire mathematical background to design for wind comfort. However, some general concepts are very useful while relatively easy to explain.

3.3.1. Atmospheric Boundary layer

Near the ground, wind speed is significantly reduced due to obstacles such as terrain, roughness, and built structures. The rougher the surface and the greater the number of obstacles, the more the wind is decelerated, increasing the thickness of the boundary layer. This boundary layer thickness refers to the vertical distance from the ground to where the wind regains its original speed. At ground level (0 m), the wind speed is zero, increasing with height until the boundary layer is surpassed (Tax 2021).

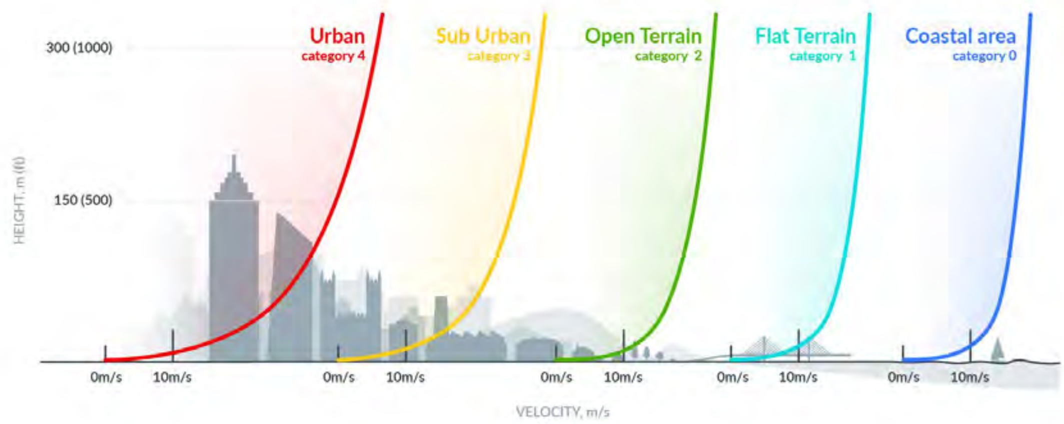


Figure 3.1: Atmospheric Boundary Layer on different terrain types (Simscale 2024).

3.3.2. Governing Equations

Wind is a fluid an as such it is well described by the Navier-Stokes equationsNavier-Stokes equations. These equations consist of the Continuity Equation as well as the momentum equation. They are fundamentally based of the principle that mass, momentum and energy are preserved through time (Garwin 2023). When running wind simulations, the computer is essentially solving these equations.

Continuity Equation

$$\nabla \cdot \mathbf{u} = 0 \tag{3.1}$$

This equation represents the conservation of mass in a fluid. Where:

- ∇*: Nabla operator, representing the gradient vector field.*
- $\mathbf{u}$*: Flow velocity vector field.*

Momentum Equation

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \sum \mathbf{F} \tag{3.2}$$

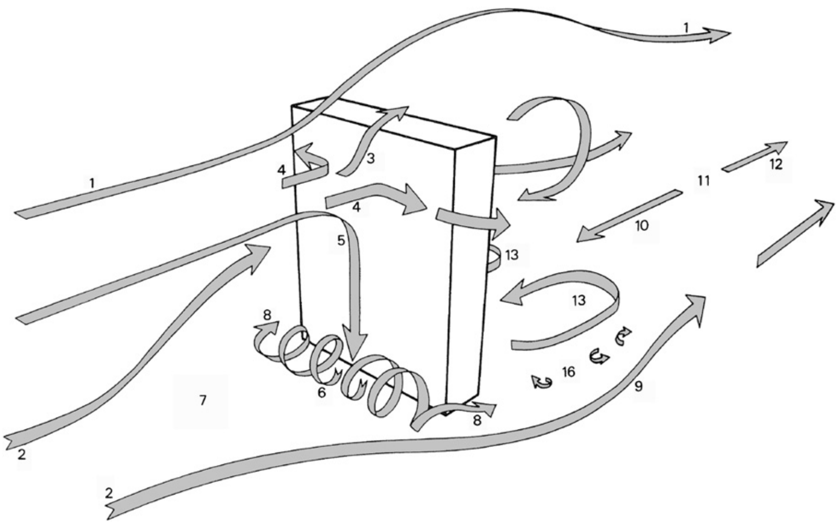
This is a rewritten version of Newton's second law, describing the movement of fluids.

Where:

- ρ*: Density of the fluid.*
- $\frac{D}{Dt}$*: Material derivative, accounting for both local and convective changes.*
- p*: Pressure within the fluid.*
- μ*: Dynamic viscosity of the fluid.*
- ∇^2*: Laplacian operator, representing the diffusion of velocity.*
- $\sum \mathbf{F}$*: Sum of external forces acting on the fluid.*

3.3.3. Wind flow around high-rise buildings

Although average wind speeds in urban areas are 40-65% lower than in rural regions due to the ABL effect, wind nuisance in cities can be more severe. This is primarily caused by the complex interaction between wind flow and varying building shapes, which results in significant local wind speed gradients. While some urban areas may experience near windless conditions, others face severe wind nuisance or even dangerous wind speeds. High-rise buildings, in particular, exacerbate these issues. As wind speeds increase with height, tall buildings intercept stronger winds. These winds are deflected over, around, and down the building surfaces, depending on the building's shape. This phenomenon generates downdrafts, frontal vortices, and corner streams at the pedestrian level, creating problematic wind conditions. The taller the building, the stronger and more extensive these corner streams become. In different urban contexts, high wind speeds at the pedestrian level might result from different wind effects. This means that while trained engineers can often make an estimated guess, every situation has to be viewed separately in its context. The following image 3.2 is often used to explain wind and summarizes the movement of wind around high-rise buildings quite well (Tax 2021).



0	Undisturbed wind	5	The larger part of the air flow in front of the building is deflected downwards
1, 2	Air flow over and around the building	6	Vortexes in front of the building; the main stream at ground level is away from the buildings
3, 4	Air flow in front of the building is partly deflected above and aside	7	Stagnation point in front of the building
8	Strongly increased wind speed at the corners of the building	9	Broad jet streams with increased velocity next to the building
10, 14	Reversed air flow behind the building	11	Stagnation point behind the building
12	Air stream in the direction of the wind behind the rear stagnation point	13	Standing vortexes behind the building
14	Increased discomfort in the reversed air stream	15	Upward-directed air streams behind the building
16	Small fast rotation vortexes	17	Edge of the "influence area"

Figure 3.2: Schematic representation of wind flow pattern around a high-rise building (Beranek and Koten 1979)

3.4. Wind Prediction through Computational Fluid Dynamics

Wind flow in practice can be predicted in 2 main ways: through experiment wind tunnels or CFD (computational fluid dynamics) simulations. Both methods have their own advantages and disadvantages, which are explained in the following section.

3.4.1. Computational Fluid Dynamics

Apart from measurements, fluid behavior can also be predicted computationally. The book "Notes on Computational Fluid Dynamics: General Principles" defines CFD as "the prediction of fluid motion and forces by computation using numerical analysis, generally extended to include heat, thermodynamics, chemistry, and solids". *In practice, this is done by solving the governing equations (Navier-Stokes equations) for every cell in a grid that includes the air around the geometry of the location to be studied and all the air that is affected. This is done iteratively. (Greenshields and Weller 2022)*

3.5. Design Strategies

While the impact of multiple design strategies on the urban wind climate has not been broadly studied, several design approaches are known to impact the wind climate around buildings. These strategies are meant to address downdrafts, frontal vortices, and corner streams differently.

3.5.1. Aerodynamic Shape

The shape and volume of a building are among the most influential parameters that architects can adjust to influence wind patterns around high-rise structures. However, while many shape modifications have been proposed, they do not differ by a lot. Generally speaking, the more a corner is rounded off, the more aerodynamic the building (Amin and Ahuja. 2010).

Modifications along the height of a building have an impact on its aerodynamic properties as well. Tapering a building breaks up vortex patterns, distributing wind loads more evenly. Twisting a building's form disrupts wind flow along its height, preventing the synchronization of vortex shedding. This reduces dynamic responses, enhancing stability (Amin and Ahuja. 2010).

3.5.2. Podium-shaped extensions & canopies

Apart from strategies that alow wind to flow more natural around buildings, it is also possible to catch downdrafts before they reach the ground in the first place. This can be done by either podium-shaped extensions or canopies. Both are often seen in literature and can be seen as effective (Tax 2021).

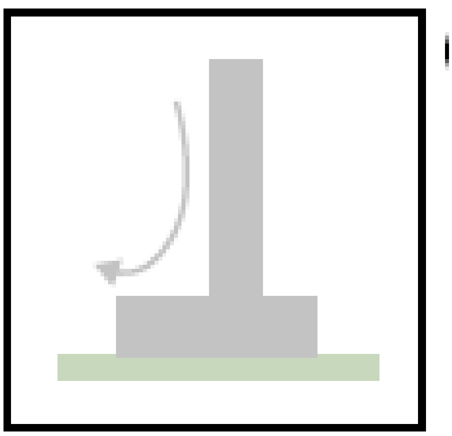


Figure 3.3: Podium-Shaped extension (Tax 2021)

3.5.3. Openings

Strategically placed openings, especially near the tops of buildings, provide pathways for wind to pass through, reducing pressure and turbulence. The Shanghai World Financial Center exemplifies this with its distinctive top opening, which alleviates wind forces while maintaining a striking silhouette. This strategy blends functional wind management with bold architectural expression (Amin and Ahuja. 2010).

3.5.4. Balconies

In the architectural field, it is generally assumed that balconies have an impact on wind patterns. However, while literature confirms that the shape and depth of balconies indeed fundamentally alter wind patterns, the effect on pedestrian height around the building is limited (Zheng, Montazeri, and Blocken 2021)

3.6. Conclusion

This chapter has outlined the theoretical context of wind behavior, prediction, and mitigation strategies. By understanding these principles, architects can design high-rise buildings that enhance pedestrian comfort and safety while maintaining aesthetic and functional integrity.

4

Workflow Development

4.1. Introduction

In this part of the research, a wind-oriented design approach is tested. At first, several design approaches are chosen in order to test their effect on wind speeds at pedestrian level. Each strategy features multiple masses and simulations in order to test how the desired effects can be achieved.

4.2. Design Strategies

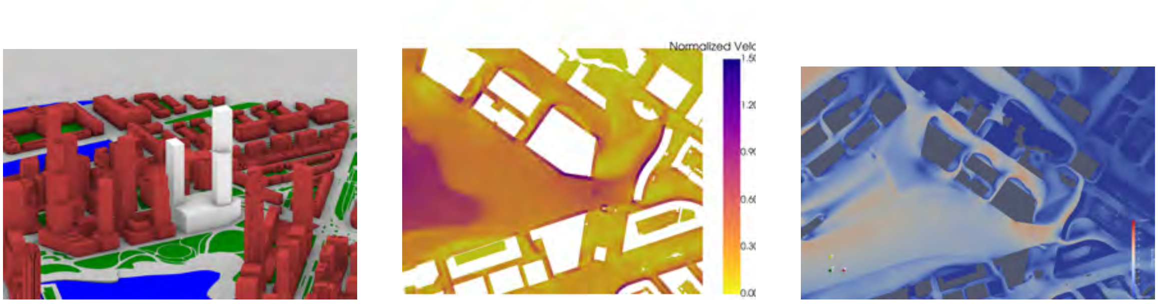
In this chapter, the effects of the height of the towers, the existence of a podium, the existence of an open floor and the shape of the towers are investigated. These strategies have been selected based on several sources as they are described in chapter 3, as well as the intuition of the author. The design strategies for which a simulation was run can be seen in table 4.1.

Design Stragegy (DS)	Implementation
1	Rectangular high-rise structures
2	Shorter rectangular high-rise structures
3	Round off towers as shown in plan by municipality
4	Remove proposed towers, keep Rotterdamse laag
5	Rectangular building, no setbacks
6	Rectangular building, 5m podium
7	Rectangular building, 10m podium
8	Open floor with a height of 6 meters
9	Open floor with a height of 12 meters
10	Circular shaped tower
11	Airfoil shaped tower
12	Lower plinth, rectangular building, 10m podium
13	rounded tower (fillet 10m)
14	rounded tower, and plinth (fillet 10m)
15	rounded plinth (fillet 10m), rectangular tower, 5m podium

Table 4.1: Studied Design Strategies

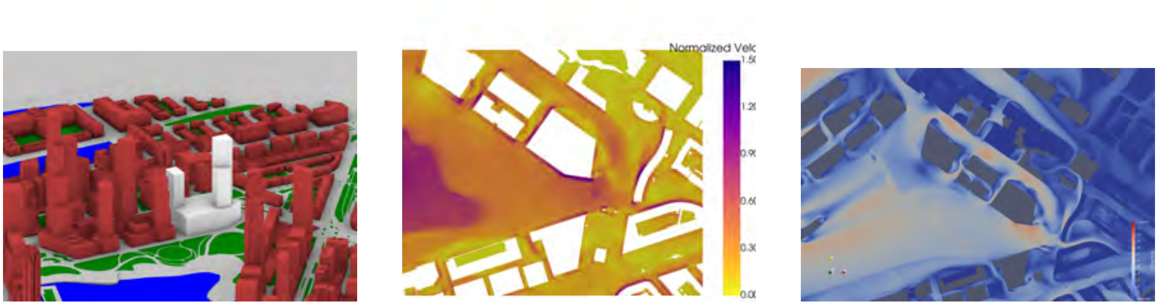
4.3. Tower height

The impact of the height of the tower was tested with DS1, DS2 and DS4. In figure 4.1, 4.2 and 4.3,we can see that there are differences between the different scenarios. Interestingly, the situation in front of the building (towards the south) does not change as much. However, the difference is large in the north and east. In the scenarios without the tower or with a lower tower, wind flows more freely around the building. The tallest variant actually reduces wind speeds to the northeast. From this, we can conclude that lowering the tower is not the best strategy for this location.



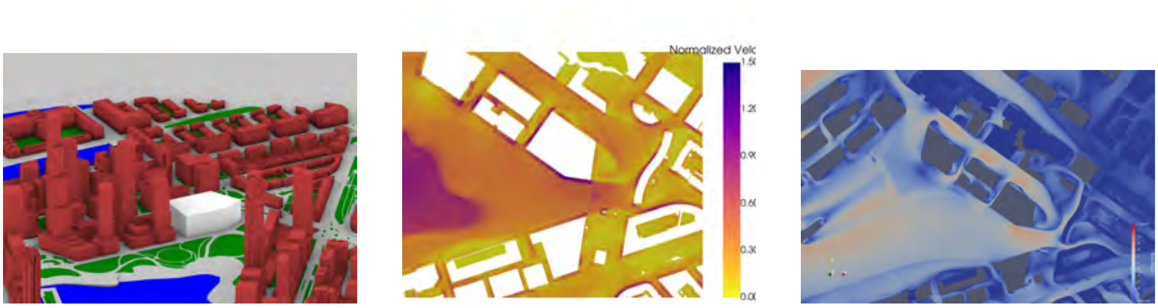
(a) Mass of DS1 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.1: DS1



(a) Mass of DS2 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.2: DS2

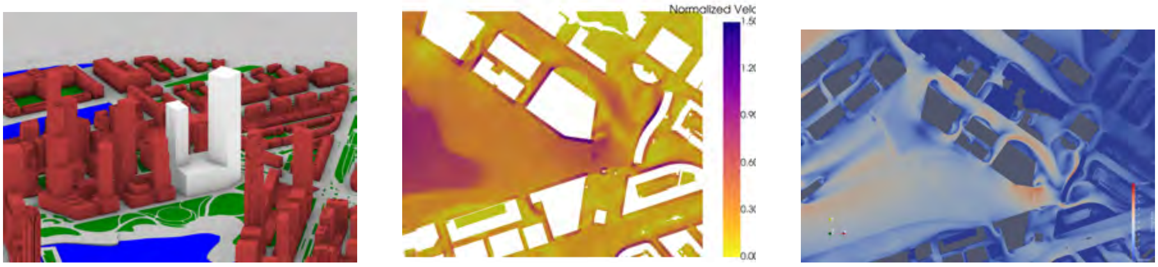


(a) Mass of DS4 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.3: DS4

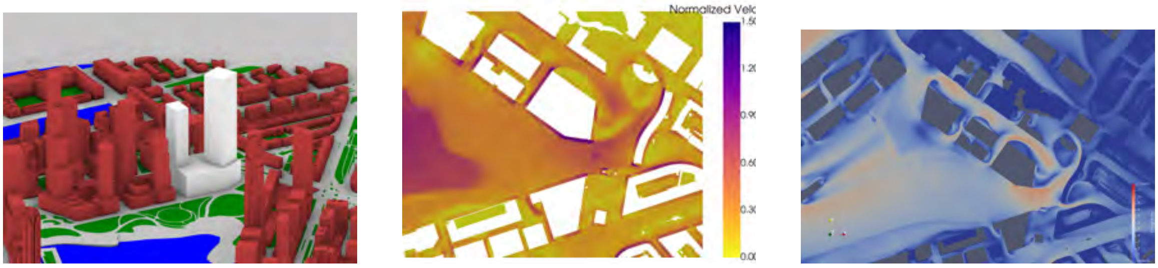
4.4. Podium

The effect of the podium is tested with DS5, DS6, DS7 and DS12. If we take a look at the normalized wind speeds for these design strategies, we can see that the impact on the windward side is minimal. However, we do see a difference on the leeward side (northeast). Increasing the size of the podium seams to have an effect. However, it might not be worth moving the tower this much for such a small effect. Furthermore, the effect of lowering the podium was tested with DS12. This seams to increase wind speeds slightly on the leeward side.



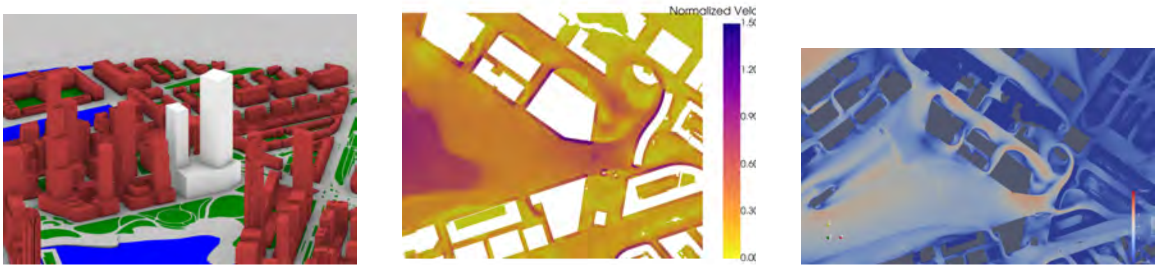
(a) Mass of DS5 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.4: DS5



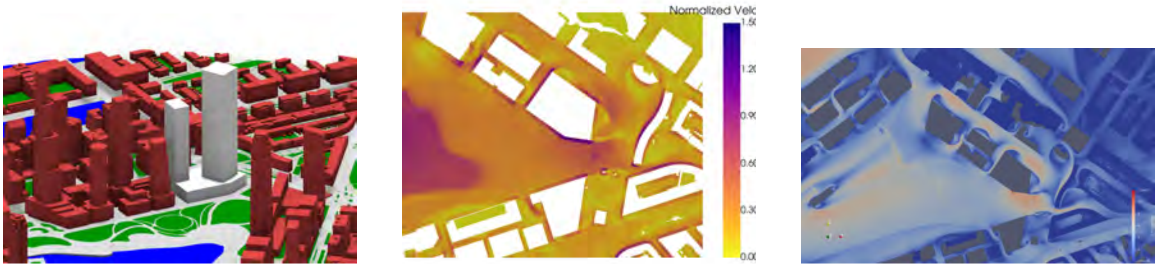
(a) Mass of DS6 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.5: DS6



(a) Mass of DS6 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.6: DS7

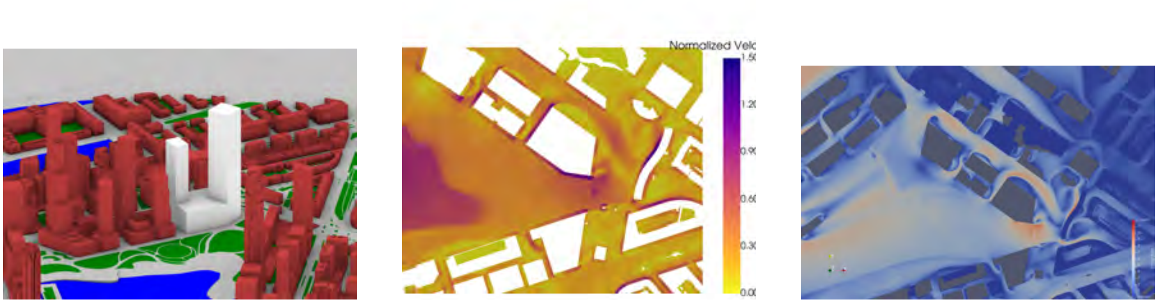


(a) Mass of DS12 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.7: DS12

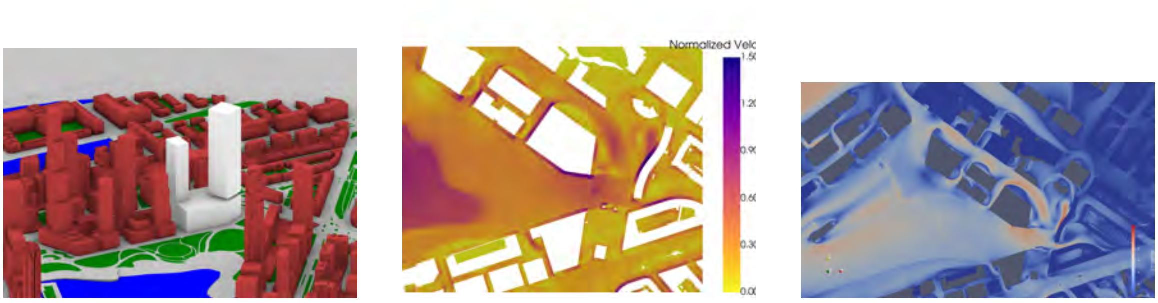
4.5. Open floor

The effect of the open floor has been tested using DS5, DS8 and DS9. When taking a look at the normalized wind speeds, we see a reduction in wind speed towards the east of the building. This is in line with the wind direction. While not as large of a difference as the podium, it is visible.



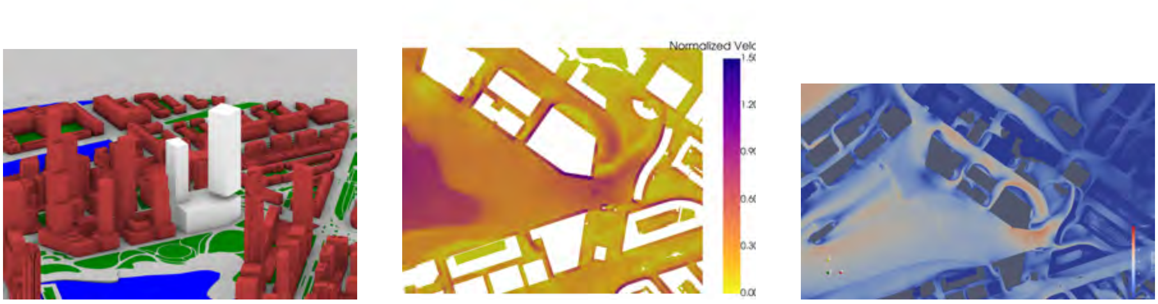
(a) Mass of DS5 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.8: DS5



(a) Mass of DS8 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.9: DS8



(a) Mass of DS9 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.10: DS9

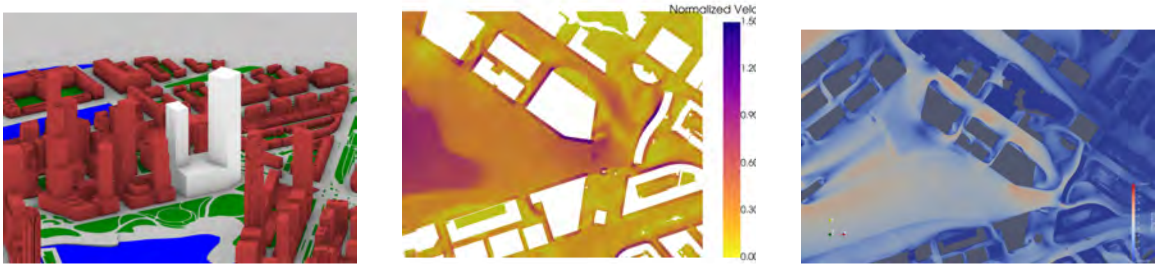
4.6. Building shape

The effect of the shape of the building is tested with DS5, DS10, DS11, DS13, DS14 and DS15. DS5 serves as a base, rectangular shape while the other strategies represent more aerodynamic shapes. DS10 is fully circular while DS11 is shaped as an airfoil. An airfoil is, according to theory, one of the most aerodynamic shapes.

If we take a look at the normalized wind speeds for these shapes, we can see that there is indeed a significant difference between the different design strategies. We can see that, while DS10 and

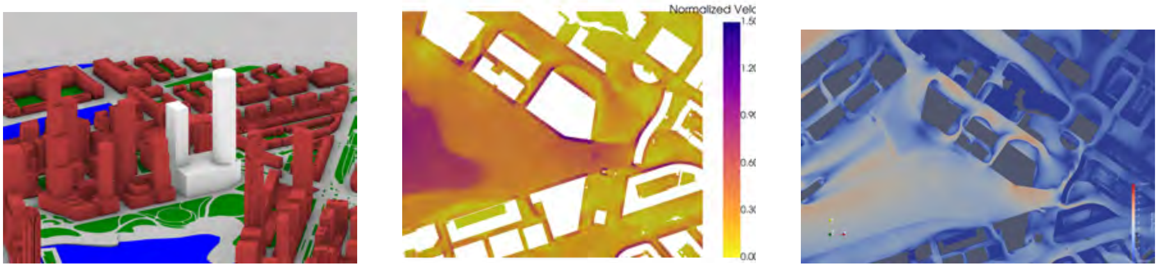
DS11 are not that different from each other, the wind wind speeds of both are lower compared to DS5. DS13 features rounded corners, which makes this design more aerodynamic then DS5, but less aerodynamic compared to DS11.

Furthermore, the effects of a more aerodynamic plinth were tested. Rounding off the plinth removes the obstacle for the wind to move around the corner, thus increasing wind speeds. on the northeastern side of the building.



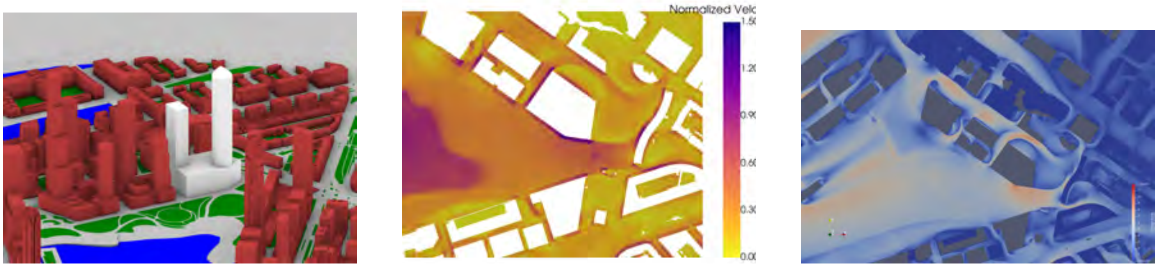
(a) Mass of DS5 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.11: DS5



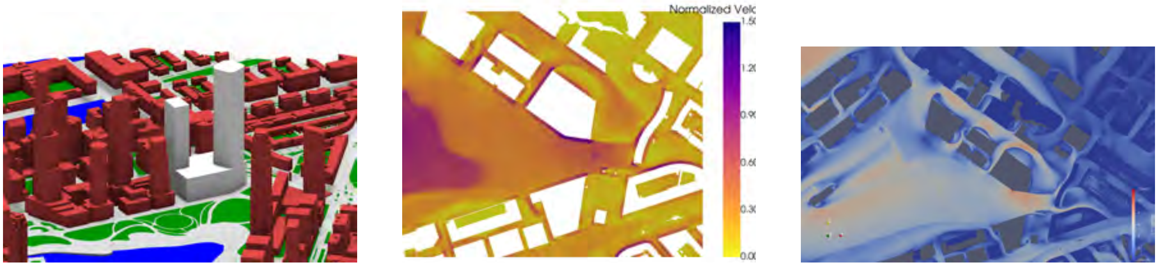
(a) Mass of DS10 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.12: DS10



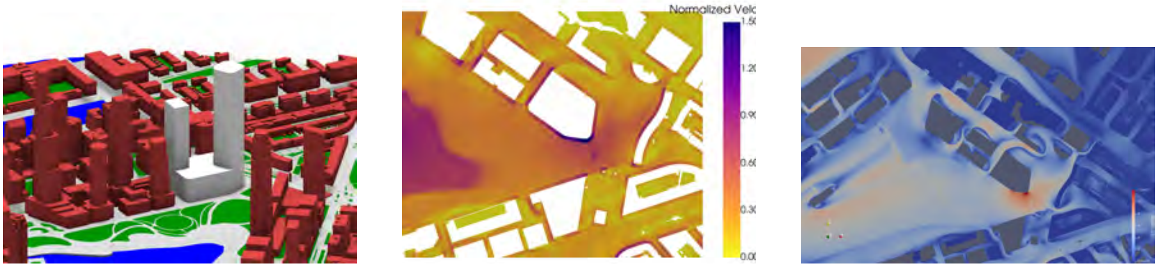
(a) Mass of DS11 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.13: DS11



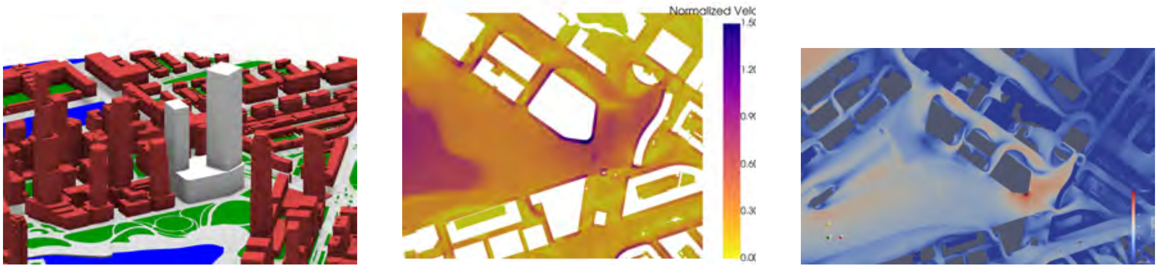
(a) Mass of DS13 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.14: DS13



(a) Mass of DS14 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.15: DS14



(a) Mass of DS15 **(b)** Normalized wind speeds (U/Uref) **(c)** Absolute wind speeds (m/s)

Figure 4.16: DS15

4.7. Conclusion

In this chapter we have seen that the shape of a building has a significant impact on the wind speeds that are measured at pedestrian height. What all results have in common, is that the difference on the windward side of the building is minimal. The largest differences are on the leeward side. It can be concluded that DS5, the most "boxy" building causes the highest wind speeds, while placing the building on a podium, creating a gap in the building or making the shape more aerodynamic reduces wind speeds. From the experiments, we can conclude that the aerodynamic shape is the most important, as we see the largest reduction in wind speeds compared to the other strategies.

5

Conclusion

5.1. Introduction

This research has demonstrated the importance of integrating wind behavior into the early design stages of high-rise buildings, particularly in urban environments like Rijnhaven, Rotterdam. By combining theoretical insights with computational simulations, the study developed a workflow that equips architects with practical tools to address wind-related challenges effectively. This has been done while answering the following research question:

How can an improved understanding of wind behavior be integrated into high-rise design strategies to enhance pedestrian comfort and safety in Rijnhaven, Rotterdam?

As well as the following design question:

How does the incorporation of a wind-based design workflow impact the design process of a multifunctional highrise building in the the urban context of Rijnhaven, Rotterdam?

5.2. theoretical background

The theoretical background establishes that wind behavior is a complex yet critical factor in high-rise design. By understanding principles such as the Venturi effect, wind-blocking effect, and urban canyon dynamics, architects can predict and mitigate adverse wind conditions. Several design strategies can be used in order to improve pedestrian wind comfort, including aerodynamic shaping, podiums, and strategically placed openings, offer practical solutions to address these challenges. However, while changing geometrical attributes of balconies has a large effect on the comfort on the balcony, it barely impacts comfort at pedestrian height. While architectural designers do not need to understand all the contents of this chapter, a basic understanding can certainly help while going through the initial stages of a design project.

5.3. Workflow development

In this chapter, several design strategies have been tested. We have seen that, out of all the design approaches, the "boxy" DS5 causes the highest wind speeds around it. The effects of the several design strategies on the windward side appear to be minimal, while the effects on the leeward facade are substantial. Making the shape more aerodynamic helps, as well as placing it on a podium.

Most of all, this chapter proves that architects should take wind into consideration while designing. The effects of different geometries are substantial on pedestrian wind comfort. However, smaller variations of the same design strategies (such as a smaller or larger podium) are minimal. Therefore, it is recommended to test a variety with large differences, as to find the strategies with the most impact for this location.

5.4. Limitations

*Due to time- computational limitations, this research was only caried out for one wind direction. Normally, similar research is caried out for at least 12 wind directions. This makes it tough to compare this project with other research, and impossible to calculate the pedestrian comfort as described by the (*NEN8100 *2006).*

5.5. Conclusion

The findings highlight that the shape of a building significantly influences pedestrian wind comfort and safety. Strategies such as incorporating aerodynamic shapes, podiums, and open floors can mitigate adverse wind effects while preserving architectural freedom. Incorporating these findings into the architectural design process for high-rise structures is vital in order to build a tower that people would like to be around.

6

Reflection

6.1. Introduction

This reflection explores the personal and academic journey I undertook during the development of my graduation thesis, Wind Driven Design. The project aimed to integrate wind behavior into early-stage architectural design decisions, particularly for a high-rise structure in the urban context of Rijnhaven. This project challenged me to step far outside my comfort zone, into the complex worlds of fluid dynamics and computational simulations. This reflection discusses my initial position, the skills I developed, the insights I gained, and how this thesis has shaped my perspective as an architectural designer.

6.2. Getting started

When I began this thesis, I had little idea of the technical complexity I was about to engage with. My background in architecture did not include any knowledge of fluid dynamices, and I barely knew how to code in python. I had never heard of OpenFOAM. Despite this, I was drawn to the topic. I was interested in the ways in which an architect can influence such an invisible force and how a designer can use it to the benefit of a pedestrian. I dove into the project with a healthy dose of naivety and enthusiasm, supported every step of the way by my research mentor, Clara, who patiently introduced me to the principles of simulation-based wind analysis.

The learning curve was steep. Early simulations crashed constantly, and generating a workable mesh felt like solving a riddle in an unfamiliar language. But slowly, I began to understand the process, appreciate the logic behind the tools, and found satisfaction in smaller and larger successes. Eventually, I was able to run several successful simulations that offered meaningful insights into wind behavior. That progress felt like a genuine achievement—not just academically, but personally. It showed me that with persistence and support, I could navigate technical terrain I once found inaccessible.

6.3. Personal insights

One of the most striking lessons I learned throughout this process is how unpredictable wind behavior can be. Initially, I assumed downdrafts would be the primary issue I would face, but my simulations revealed otherwise. The most significant effects occurred on the leeward side of the buildings—an area I had not expected to be so problematic. In hindsight, these results made sense, but they also underscored the limits of relying solely on intuition or even literature.

This experience taught me a critical lesson: in wind design, assumptions are dangerous. Real understanding requires testing—whether through wind tunnel experiments or CFD simulations. This realization has reshaped how I view the design process. It's not enough to trust in general principles; context-specific testing is essential to truly understand how a design will behave in the real world. This insight has made me more cautious, but also more curious and analytical in my design thinking. Furthermore, it took away my fear of calculations and simulations.

6.4. Design process

After completing the research phase, I transitioned into the design phase, using the insights from my simulations to inform my design process. Since the site and program of requirements remained consistent, I could directly integrate my findings into the design strategy. This felt like a natural progression—from research to application.

However, the integration wasn't always as straightforward as expected. Some hypotheses I had going into the design phase didn't hold up under further simulation. For instance, I had assumed that rounding off both towers would reduce wind speeds on the leeward side. While this worked for the southeast tower, it had the opposite effect on the northwest one. Surprisingly, the wind conditions actually worsened, leading me to reverse the rounding and opt for a squared-off shape instead.

This phase reminded me that even well-reasoned assumptions need to be validated. Design is an iterative process, and wind adds a layer of complexity that requires constant re-evaluation and flexibility.

6.5. Design recommendations

Based on the findings of my thesis, I can reaffirm that architects must incorporate wind considerations in the earliest stages of the design. Waiting until the final stages to address wind issues—when the design is already fixed—often leads to inefficient and visually disruptive solutions. Starting earlier not only improves pedestrian comfort and safety, but also preserves architectural freedom.

During this project, I explored a wide range of massing strategies to test their impact on wind behavior. This broad, comparative approach proved effective: even when the tested forms didn't align perfectly with the final design, they still offered valuable insights. By identifying general patterns and sensitivities, architects can make more informed decisions early in the process, adapting and refining their designs with greater confidence.

6.6. Future research

Due to limited computational resources and time constraints, this research was restricted to a single wind direction and one specific location—Rijnhaven in Rotterdam. However, wind conditions vary significantly depending on orientation and context. To develop a more universally applicable design approach, future research should expand to include multiple wind directions and diverse urban environments.

By broadening the scope, it would be possible to create a more comprehensive designer's guide that could be used across different sites and cities. Such a guide would empower architects to address wind issues with more confidence and precision, even without deep technical knowledge of CFD. This research could serve as a foundational step in that direction.

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