MASTER

Numerical study of wind energy harvesting by the Strata Tower analysis of current performance and design improvements

Kompatscher, K.

Award date:
2015

Link to publication
Numerical study of wind energy harvesting by the Strata Tower
Analysis of current performance and design improvements
PREFACE

I would like to express my sincere appreciation to several people for their help during this project.

First of all, I want to thank prof.dr.ir. Bert Blocken and dr.ir. Twan van Hooff for their inspirational lectures and expressed enthusiasm that got me into this research area in the first place. Of course, I want to thank them also for their monthly input of valuable knowledge and criticism that brought the best out of this research.

I want to thank my daily supervisors ir. Adelya Khayrullina and ir. Alessandro Pizzoferato for their faith and support in my abilities, being able to ask them anything, and receiving valuable answers.

My sincere thanks goes out to my friends at the Built Environment – for the coffee breaks, input in the subject matter, and being able to let me refocus – and to my friends outside university life for their friendship and personal care during dinners and late nights.

I also want to express my gratitude to the employees of the BPS Lab for their help with server shutdowns, laptop problems and the accompanied coffee breaks with all the above issues.

Lastly, my family – mom, dad and brother – and Joris, thank you.

Karin Kompatscher

Eindhoven, February 2015
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Abstract

Depletion of fossil fuels and their severe influence on the environment such as the extra greenhouse effect, smog and acid rain triggers research towards the use of sustainable and renewable energy resources. In order to reduce the use of finite resources, several targets are set by, for instance, the European Commission, to be met by 2020. Many stakeholders are involved in the process of searching solutions for energy-efficient buildings.

This project is focused on one of these energy-efficient buildings; the Strata tower. The Strata tower is a 148 meters high-rise residential building on the south bank of the Thames, London. Three horizontal-axis wind turbines are integrated in the sloped roof by means of three cylindrical tubes. Several pre-planning studies have been carried out and concluded that the three wind turbines would be feasible to integrate in the roof of this high-rise building. After completing construction in 2010, the wind turbines are reported to not operate as they should. The research objectives of this study are the following:

- Investigate why the wind turbines are not operating,
- Investigate if the cross-section of the wind turbine encasing could be optimized in order to make the wind turbines operative,
- Determine what would be a proper design solution for this case study,
- Investigate the possibility to increase the wind potential by modifying the geometry of the building.

The study consists of a literature study in combination with Computational Fluid Dynamics (CFD) simulations to carry out a numerical study for several building configurations.

A Computer Aided Design (CAD) model of the Strata tower, with the three openings in the roof, was generated to assess the wind potential by CFD simulations. A wind speed amplification is expected through the passages due to the channeling effect. The extent of the amplification implies an increase or decrease in wind energy potential and is therefore an important evaluation parameter in this study.

It can be concluded from this study that an increase in wind energy potential can be achieved by adopting design solutions that alter the cross-section of the wind turbine openings (i.e. design solutions similar to using shrouded wind turbines). Three wind directions are investigated for the Strata tower. The difference in wind energy potential evaluated for the three different wind directions is not significant. A large increase in wind energy potential can be achieved if the wind is coming from the opposite to the prevailing wind direction. Indeed, in this case, the sloped roof channels the wind towards the wind turbine openings. Besides the design solutions, the effect of the height of the openings is investigated. It can be concluded that lowering the position of the openings to 70% and 10% of the total building height, does affect the wind energy potential. An increase of the amplification factor is obtained by lowering the position of the openings to 70% of the total building height (stagnation point). On the other hand, a decrease in wind energy potential is obtained by lowering the openings to 10% of the total building height.
General information

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Document title: MSc thesis
Project title: Numerical study of wind energy harvesting by the Strata Tower: analysis of current performance and design improvements
Date: 25 March 2015
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1 Introduction

This chapter introduces the topic of this study through a problem statement, objectives that will be met during this research, and the methodology that will be used during this research.

1.1 Problem statement

Global warming and climate change are effects of the greenhouse gas emissions. The gases composing the Earth’s atmosphere can absorb or entrap the solar radiation, causing an increment in the temperature. Human activities over the past centuries most likely contributed to the increase of the greenhouse effect.

Figure 1-1 depicts the global warming and CO$_2$ emission over the past 130 years. A steep increase in global temperature was experienced in the last 50 years as well as a significant growth of the atmospheric CO$_2$ concentration. This increase can be caused by human-produced greenhouse gases.

Though the processes of global warming and climate change are difficult to stop, it is necessary at least to decelerate them in order to continue the human lifestyle as it is known to the world’s society.

Den Elzen et al. (2013) provides an overview of the regions with the highest emissions of greenhouse gases. Though China and the United States of America lead the ranking as single countries, the European Union is the second runner up. Therefore the European Commission (2010) set three targets to reduce the emission of greenhouse gases by raising the share of the EU energy consumption produced from renewable energy sources and by improving the EU’s energy efficiency. These 20-20-20 targets to be met by 2020 are:

- 20% greenhouse gas emission reduction,
- 20% share of renewable energy sources,
- 20% improvement in energy efficiency.

![Global Temperature and Carbon Dioxide](image)

**Figure 1-1.** Global annual average temperature measured over land and oceans. Red and blue bars indicate temperatures above and below the 1901-2000 average, respectively. The black line shows the atmospheric concentration of carbon dioxide in parts per million (National Climatic Data Center, 2014).

One of the targets shows the desire to increase the share of renewable energy sources in the upcoming years. Renewable energy sources are making use of infinite sources such as solar and wind power. According to Figure 1-2 the share still needs to increase by 7% since 2011 to achieve the goal of 20% by 2020.

![European Share of Renewable Energy Sources](image)

**Figure 1-2.** European share of renewable energy sources in % of the total energy demand (EU28) (European Commission Eurostat, 2014).
The European Renewable Energy Council (2011) provides a renewable energy sources roadmap available for every European country. This roadmap contains the National Renewable Energy National Plans (NREAPs). According to these plans, one third of the energy will be generated by renewable energy sources by 2020. Onshore and offshore wind energy will constitute 14% to the energy production (Figure 1-3).

Aside from offshore and onshore wind farms, wind turbines are infiltrating the urban landscape more often. This offers the advantage of extracting wind energy directly in the places where electricity is demanded, avoiding transportation costs. This is an example of how society can reduce carbon emissions by limiting its dependency from traditional energy sources.

The research discussed in this master thesis focuses in particular on the assessment of the wind energy potential through passages in high-rise buildings. Yuen et al. (2004) performed a study on the efficiency of multiple wind turbines installed in a high-rise building in the built environment, defining it as a “building integrated wind farm”. They concluded that renewable energy can be generated from urban areas. Therefore, buildings can be designed to increase the wind energy potential and to integrate wind turbines.

Aside from conclusions of the study of Yuen et al. (2004), a few remarks need to be made. Integrating wind turbines into buildings results in critical conditions such as resonance occurring due to the variable loads acting on the wind turbine. Moreover, mechanical and electrical integration is often costly and difficult.

The shape of a building plays a significant role in the energy yield. For instance, the roof shape has a large impact on the wind flow around and over the roof. Abohela et al. (2013) provided an overview of different roof types for high-rise buildings and their advantages and disadvantages for wind turbines installed on the roof. The research of Abohela et al. (2013) concluded that different roof shapes can increase the energy yield by 56.1%.

Campbell & Stankovic (2001) designed several basic high-rise buildings with integrated wind turbines and performed wind tunnel tests with scaled models of these designs. Their research shows an increase in wind energy potential for a wind turbine mounted between two buildings at a certain height.

The different studies (Yuen et al., 2004; Abohela et al., 2013; Campbell & Stankovic, 2001), mentioned in the previous paragraphs show the feasibility of harvesting wind energy from the urban environment. Aspects such as building geometry, roof shape and placement of the wind turbines need to be taken into account while designing a high-rise building with integrated wind turbines.

1.2 Case: Strata tower, London

BFLS architects accepted the challenge to design a high-rise building with integrated wind turbines. The Strata SE1 tower (Strata tower/ Razor building) (Appendix A), located on the south bank of the Thames in London, is the first residential tower with three integrated wind turbines. The 148 meters tall building provides 408 residential apartments suitable for one thousand residents. The energy harvesting from the three wind turbines installed in the roof should be able to provide 8% of the total energy consumption of the Strata tower (BDSP Partnership, 2005). The building was completed in 2010 after three years of construction. Aside from the design and construction, several pre-planning assessments were done about the wind turbines and the geometry of the building. Several studies (BDSP Partnership, 2005; Ramboll, 2006; RWDI Consulting Engineers, 2007) have been performed prior to the construction of the high-rise tower.
Although the previously conducted studies (Rambøll Danmark A/S (2006), RWDI Consulting Engineers (2007)) conclude that it is feasible to integrate three wind turbines in the roof shape of the Strata tower, it is reported that the wind turbines are not operating\(^1\). This triggered this research on possible design solutions to improve the power extracted from the turbines integrated in the Strata tower.

### 1.2.1 Previous studies

Several studies have been performed before the construction of the Strata tower, to assess the feasibility of installing wind turbines on this building. This chapter will elaborate on these studies. Three main studies have been performed: a pre-planning assessment for a wind potential study (BDSP Partnership, 2005), a feasibility study using Computational Fluid Dynamics (CFD) and wind tunnel experimental data (Rambøll, 2006) and an experimental study (RWDI Amenos, 2007).

The wind potential study (BDSP Partnership, 2005) focuses mainly on the wind potential of the wind turbines and on optimizing the properties of the wind turbine regarding the energy production. This study concludes the following:

- \(\text{The proposed scheme could, if executed well, inaugurate a new wave of renewable energy integration in buildings.}\)
- \(\text{The energy yield of the proposed scheme could be significant and enhanced further by the shroud, which must then be aerodynamically optimized.}\)
- \(\text{It is possible to supply a significant quantity of energy with an optimized scheme. The performance could then be superior to free-standing machines.}\)
- \(\text{Wind can potentially power an entire lighting system in the building, assuming always that the building is inherently energy efficient in terms of demand.}\)
- \(\text{Application of three wind turbines at the top of Castle House is substantial, but not an insurmountable task with important environmental benefits.}\)
- \(\text{The carbon emission reduction is significant, whilst expected ‘energy payback’ (energy produced by WTs versus energy used in their manufacture, transport and installation) could be less than a year.}\)

The above conclusions are drawn with the assumptions that the three wind turbines are able to yield 45-100 MWh annually and that their mutual aerodynamic interference is negligible. BDSP Partnership (2005) states that the turbulence effects and flow separation are negligible.

Rambøll Danmark A/S (2006) performed a CFD feasibility study on the shape of the building which they called Castle House, named after the previous building on that particular site. This study focused mainly on the flow through the separate tubes and the acoustical interference of the wind turbines (Figure 1-4).

In the feasibility study of Rambøll, the CFD study was verified by wind tunnel experiments. The entire building has been modeled and simple building blocks have been used to represent the surroundings.

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shedding can occur when the wind turbines are operating.

Rambøll Danmark A/S (2006) main conclusions for this study are as follows:

- ‘It is feasible to install three wind turbines on top of Castle House.
- The noise level on the top floors of Castle House exceeds the criteria of 42dB. This should be handled by mitigating the noise from the turbine, i.e. by reducing the tip speed of the rotor and insulating the Venturi tubes.’

Another experimental study (RWDI Amenos, 2007) focuses on the mean pressures acting on the Strata tower. The pressure distribution of the Strata tower was analyzed by means of wind tunnel testing. Several pressure taps were added along the surfaces of the model to evaluate the pressure coefficient. This study, compared to the one of Rambøll Danmark A/S (2006), offers a more detailed surrounding environment (Figure 1-5). This study offers a higher level of accuracy compared to those previously mentioned as it takes into account the urban environment around Strata tower. The pressure coefficient data obtained from this study could be used for validation. Concluding remarks from RWDI Anemos (2007) are as follow:

- Extract vents on the roof of the tower and north façade would experience favorable negative pressures for significant periods of time.
- Intake vents on the south side of the façade would experience favorable positive suction for significant periods of time.
- The above mentioned arrangement will aid natural ventilation in the residential units.
1.2.2 Wind conditions

The prevailing wind direction for South London is from the southwest (Figure 1-7) according to the data collected from the weather station at the Heathrow Airport.

The axes of the Strata tower openings are not directed to the southwest prevailing wind direction. Rambøll Danmark A/S (2006) recommends installing the tubes and wind turbines in the prevailing wind direction for an optimal energy yield. The technical drawings of the Strata tower show that this has not been done (Appendix A). In figure 1-8 the direction of the axes of the turbines integrated in Strata Tower is identified by the orange line. The axes of the turbine are rotated by 15° degrees relatively to the prevailing wind direction.

Figure 1-7. Prevailing wind direction for Heathrow Airport (Meteorological Office UK).

The axes of the Strata tower openings are not directed to the southwest prevailing wind direction. Rambøll Danmark A/S (2006) recommends installing the tubes and wind turbines in the prevailing wind direction for an optimal energy yield. The technical drawings of the Strata tower show that this has not been done (Appendix A). In figure 1-8 the direction of the axes of the turbines integrated in Strata Tower is identified by the orange line. The axes of the turbine are rotated by 15° degrees relatively to the prevailing wind direction.

Figure 1-8. Heathrow wind direction and axis of Strata SE1 openings (orange line) (Rambøll Danmark A/S, 2006).

1.3 Research objectives

Based on the concluding remarks of the earlier conducted research about Strata Tower, the following conclusions can be drawn:

- The application of three wind turbines at the top of Castle House is substantial, but not an insurmountable task with important environmental benefits,
- The carbon emission reduction is significant, whilst the expected energy payback could be less than a year,
- It is feasible to integrate three wind turbines on top of the Strata tower based on wind tunnel experimental data and CFD evaluative data for possible integration of the wind turbines,
- The noise level exceeds the criteria of 42 dB and should be reduced by mitigating the noise from the turbine.

Non-professional observations state that the wind turbines are not operating (frequently). The reasons for this vary from acoustical nuisance\(^2\) to the maintenance costs\(^3\).

\(^2\) http://londonist.com/2010/03/noise_fears_could_stall_strata_turb.php
\(^3\) http://www.london-se1.co.uk/forum/read/1/168930/page=2
Quote forum: ‘I was chatting to someone who lives there and they said that the reason they don't turn is because they realized the cost of maintaining the turbines after they were installed was too much. Makes sense as someone would have to foot a massive bill to keep them running safely. It's a shame if true.’

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The conclusions of the earlier conducted research in combination with the observations that have been made nowadays result in the following research question:

**Why are the three wind turbines on top of the Strata tower not working properly and how is it possible to improve the performance by modifying the geometry and the position of the openings?**

To answer this main question several sub questions need to be answered:

- What is needed for a wind turbine to operate properly in the built environment?
- Which studies have already been performed on integrated wind turbines and on the turbines installed on top of the Strata tower?
- What is the influence of the surroundings on the performance of the turbines?
- What is the influence of the geometry of the openings and of their placement?
- Which duct configuration allows higher wind potentials?
- Which expedients can be adopted to make the wind turbines operational?
- Can guidelines be created for future high-rise buildings with integrated wind turbines?

The first two questions have been partially answered in this introduction to obtain an insight in the subject of this research. The remaining questions will be answered by the literature and numerical studies conducted.

### 1.4 Methodology

This research consists of three fundamental steps: a literature study, a validation study and a (CFD) case study (Figure 1-9).

#### 1.4.1 Literature study

The main goal of the literature study is to gain a first insight about wind turbines integrated in high-rise buildings and the use of CFD tools to predict the flow field around such buildings. During the literature study a case study has been analyzed to get accustomed to the software tools Gambit and FLUENT.

#### 1.4.2 Validation study

In order to obtain the correct input variables for the computational model, including boundary conditions, cell size and turbulence model, a validation study has been performed. Reference data for the validation are obtained from the wind tunnel experiments of Rambøll Danmark A/S (2006). However, since the data...
available from the Rambøll study is limited, the data obtained from the computational study performed by RW DI Anemos Consulting Engineers (2007) are also used. RW DI Anemos Consulting Engineers (2007) have investigated the surface pressures along the envelope of the Strata tower. Pressure taps were put on the roof and façade of the Strata tower to obtain mean pressure coefficients.

The validation study was performed by analyzing the basic configuration of the Strata tower. The basic configuration is the Strata tower as it has been completed in 2010. Further configurations have been analyzed adopting the CFD setup validated with the base case and are described in the following section.

1.4.3 Case study

CFD simulations of the base model have been performed to validate the numerical setup. This was used to analyze the other configurations analyzed in this document. The surroundings were modeled by simplifying the building blocks in previous performed studies (Rambøll Danmark A/S, 2006). This way, it was possible to quantify the influence of the surrounding buildings. During this study the surroundings are implicitly modeled by means of the roughness height.

1.4.3.1 Configurations

In the previous paragraph several possible design improvements for the openings were proposed. An overview of the various configurations can be found in Appendix B - Table 9-1.

*Base case*

The geometry of the Strata tower, in its current appearance, represents the base case for this research. It represents the first studied configuration. The original geometry was improved by adding a nozzle (i.e. Venturi tube) and diffuser in order to take advantage of the pressure conditions, as usually done for shrouded wind turbines (Figure 1-10).

Figure 1-10. Different design solutions concerning the cross-section of the central wind turbine opening. Left; base case. Center; nozzle configuration. Right; diffuser configuration.

*Openings at 70% of building height*

The stagnation point of a wind flow on a building façade usually occurs between ²/₃ and ³/₄ of the total building height (Peterka et al., 1985). In this case the stagnation point is considered at 70% of the total building height. Wind flow that reaches the building at the stagnation point is separated into sideward and downward wind flows. The configuration of Strata tower (Figure 1-11; center shape, where H_b is the total building height) is expected to force the entire wind flow to pass through the wind turbine openings to

Figure 1-11. Different design solutions concerning the placement height of the wind turbine openings. Left; base case, openings at 95% of total building height (H_b). Center; openings at 70% of H_b. Right; openings at 10% of H_b.
avoid separation and follow the path that offers the lowest energy losses.

**Openings at 10% of building height**

Placing the wind turbine openings at the bottom of the building is a way to investigate if the placement height of the openings affects the performance of the wind turbines (Figure 1-11; right image). By placing the openings at the lower part of the façade, the downward flow can be used to increase the wind velocity in the openings.

**Diffuser**

Another configuration (Figure 1-12) comprises a diffuser at the end of the openings in order to increase the wind potential. The increase of wind speed by means of a diffuser is broadly investigated in literature (e.g. Kosasih & Tondelli, 2012) and used for the shrouded wind turbines.

![Figure 1-12. Diffuser modeled without the building present.](image)

1.4.3.2 Wind directions

Several wind directions are investigated (Figure 1-13): (1) 0° - direction of the openings axes, (2) 15° - prevailing wind direction for London based on the meteorological data from Heathrow airport, (3) 180° - reverse to 0° wind direction as suggested by van Dronkelaar (2011).

![Figure 1-13. Investigated wind directions in a schematic top view.](image)
Some main features behind this research project will be briefly explained and discussed in this chapter of the report.

Firstly, the properties and behavior of wind in rural and urban areas will be explained. Background information will be given on possible solutions for harvesting wind energy and how several of these solutions are implemented into the urban area.

Lastly, guidelines for the use of Computational Fluid Dynamics (CFD) as well as the boundary conditions adopted for this study will be explained.

2.1 Wind flow

This subparagraph explains the behavior and properties of wind flow by creating a distinction between rural and urban areas.

2.1.1 Rural areas (uniform surface)

Meteoterm, the terminology database of the World Meteorology Organisation (WMO), defines wind as an air motion in –unless specified otherwise– horizontal direction relative to the Earth’s surface. (Wind) speed is defined by the ratio of the distance covered by the air to the amount of time it takes to cover this distance. The wind velocity is specified as a two-dimensional vector quantitatively defined by the wind speed and the wind direction.

The Earth’s surface roughness influences the wind in the atmospheric boundary layer (ABL). Wind decelerates close to the Earth’s surface due to friction force, reaching a null value on the surface itself. The ABL height ranges from 50 meters in stable conditions to approximately 1 kilometer in unstable conditions. This height is influenced by the temperature gradient in the lower atmosphere and the roughness of the surface (Figure 2-1). At low altitude, e.g. 10-20% of the ABL, the wind flow is highly turbulent and defines the so called “atmospheric surface layer”. The wind speed at these altitudes depends mainly on the roughness of the Earth’s surface (Verkaik, 2006).

Obstacles to the wind flow, such as buildings or vegetation, cause an overall reduction in the wind speed and an increment of the turbulence intensity in the surface layer. The deceleration rate and the increase in turbulence depend on the intensity of the disturbance to the flow.

All the obstacles to the flow can be modelled as Earth’s surface roughness, as explained in the previous paragraph. The roughness can be described by the aerodynamic roughness length $y_0$ and the drag coefficient $C_D$ (Wieringa, 1993). Drag coefficient $C_D$ quantifies the resistance of an object in a fluid environment with the following relation:

$$C_D = \left( \frac{u_{ABL}^*}{U} \right)^2$$ (1)

$u_{ABL}^*$ - friction velocity of the ABL (m/s),
$U$ - wind speed (m/s).

Figure 2-1. Atmospheric Boundary Layer height depending on surface roughness.
The aerodynamic roughness length is a height-independent parameter and defines the surface roughness observed by the flow. \( C_D \) is a height-dependent variable, which makes \( y_0 \) more preferred as a basic descriptive roughness parameter whereas \( C_D \) is often preferred for modeling purposes depending on the value of \( y_0 \) (Wieringa, 1992). \( y_0 \) is categorized into the following classes (Table 2-1).

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>( y_0 ) (m)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Open sea</td>
<td>0.0002</td>
</tr>
<tr>
<td>2</td>
<td>Mud flats, snow; no vegetation, no obstacles</td>
<td>0.005</td>
</tr>
<tr>
<td>3</td>
<td>Open flat terrain; grass, few isolated obstacles</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>Low crops; occasional large obstacles, ( x/H &gt; 20 )</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>High crops; scattered obstacles, ( 15 &lt; x/H &lt; 20 )</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>Parkland, bushes; numerous obstacles, ( x/H = 10 )</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>Regular large obstacle coverage (suburb, forest)</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>City center with high- and low-rise buildings ( \geq 2 )</td>
<td></td>
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</tbody>
</table>

Richards & Hoxey (1993) mention the log-law equation that expresses the wind velocity profile over a large surface of uniform roughness for thermally neutral stratification;

\[
U(y) = \frac{u^*_{ABL}}{\kappa} \cdot \ln \left( \frac{y + y_0}{y_0} \right)
\]

(2)

\( u(y) \) - mean wind speed at height \( y \) (m/s),
\( u^*_{ABL} \) - friction velocity of the ABL (m/s),
\( \kappa \) - von Karman constant (=0.42 (-)),
\( y_0 \) - aerodynamic roughness length (m).

The mentioned friction velocity shows a relation to the shear stress factor \( \tau_0 \), expressed by the following equation;

\[
u^*_{ABL} = \sqrt{\tau_0 / \rho}
\]

(3)

\( u^*_{ABL} \) - friction velocity of the ABL (m/s),
\( \tau_0 \) - shear stress (-),
\( \rho \) - air density (kg/m\(^3\)).

The log-law is used to determine the mean horizontal wind speed over rough surfaces with vertical deviations (e.g. terrain classifications as mentioned in Table 2-1) above a height where individual objects have no more impact on the flow. The result is a description of the vertical wind speed profile after passing by a rough terrain with a fetch larger than 5 kilometers (i.e. fully-developed wind profiles). Such a vertical wind speed profile is applicable as an inlet boundary condition for wind tunnel studies and computer simulations.

Another way to describe the mean wind speed profile consists of using the power law approximation (Petersen et al., 1998).

\[
\frac{U(y)}{U_{(ref)}} = \left( \frac{y}{y_{(ref)}} \right)^\alpha
\]

(4)

\( U(y) \) - wind speed [m/s] at height \( y \), (m),
\( U_{(ref)} \) - wind speed [m/s] at reference height \( y_{(ref)} \), (m),
\( \alpha \) - power law exponent (-).

This law describes accurately wind profiles averaged over time periods from 10 to 60 minutes. Petersen et al. (1998) state that the applicability of the power law should be limited to neutrally stable boundary layers in equilibrium over uniform terrain. The exponent of the power law depends on the height and surface roughness. However, the power law produces larger errors when describing the flow close to the surface of the Earth. In this case, the log-law is preferred and it is adopted for the study reported in this document.

A way to describe turbulent flows in wind engineering is to solve numerically the Reynolds-Averaged Navier-Stokes (RANS) equations. These represents the balance equations for the physical properties involved in the study. They include, for this case, at least one vector equation for the momentum and one scalar equation for the mass. The physical properties are averaged over the time, leading to statistically steady solutions (Franke et al., 2004). However, averaging the equations leads to additional terms associated to the fluctuations of velocity. These terms, which
increase the number of unknown physical properties, are called “Reynolds-stresses”.

To describe these Reynolds-stresses as a function of the mean flow variables, a number of turbulence models have been developed. These turbulence models can be divided in two categories based on the approach used to model the turbulence.

The first approach is based on the eddy viscosity assumption, which models turbulent stresses as derivatives of the mean velocity. Additional equations are solved for turbulent kinetic energy (k), the dissipation rate (\( \varepsilon \)) or other equivalent quantities.

The second approach is based on solving additional transport equations for each Reynolds-stress and the dissipation rate of the turbulent kinetic energy. This approach is known as the Second Moment Closure (SMC) or Reynolds Stress Modeling (RSM).

A widely used model in wind engineering is the \( k-\varepsilon \) turbulence model (Laudner & Spalding, 1972). Two more transport equations are added to the RANS equations to close the problem. These equations describe the “turbulent kinetic energy” \( k \), which measures of the kinetic energy associated to the velocity fluctuations, and the “dissipation rate” \( \varepsilon \), i.e. the rate of conversion of turbulent kinetic energy to thermal energy caused by the work done by the smallest eddies in the flow against viscous stresses. These variables are defined by the following equations by Laudner & Spalding (1972):

\[
k = \frac{1}{2} u' u'_i
\]  
\[
\varepsilon = \nu \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_j}{\partial x_i}
\]

Main downsides of adopting the (standard) \( k-\varepsilon \) turbulence model are the overestimation of the turbulent kinetic energy at stagnating flows and the underestimation of the separation and recirculation zones on the windward side. These errors are widely known and can be avoided, at least for wind engineering flows, by using a fine calculation grid (Blocken & Carmeliet, 2006). In order to improve the standard \( k-\varepsilon \) model, several other turbulence models were developed, e.g., Yahkot & Orszag (1986) introduced the RNG \( k-\varepsilon \) model and more recently, Shih et al. (1995) introduced the Realizable \( k-\varepsilon \) model.

Another two equation turbulence model is the standard \( k-\omega \) model. It is based on the Wilcox \( k-\omega \) model (Wilcox, 1998) and has several adjustments (i.e. low-Reynolds-number effects). The specific dissipation rate \( \omega \), which determines the scale of the turbulence, is expressed as:

\[
\omega = \frac{\varepsilon}{k \beta'}
\]  

where:

- \( \omega \) - specific dissipation rate (1/s),
- \( \varepsilon \) - turbulence dissipation rate (m\(^2\)/s\(^3\)),
- \( k \) - turbulent kinetic energy (m\(^2\)/s\(^2\)),
- \( \beta' \) - model constant (\( \beta' = C_\omega = 0.09 \))

A variation of the standard \( k-\omega \) model is the SST \( k-\omega \) model (Menter, 1994). This turbulence model combines the original Wilcox model (1988) for use near walls and standard \( k-\varepsilon \) model away from walls in the free flow field. In this study the SST \( k-\omega \) model is applied as the recommended model for the validation study.

### 2.1.2 Urban areas

Modeling wind flow in rural areas (uniform surface) or areas with low terrain classification for the aerodynamic roughness shows several aspects that need to be taken into account. In order to model obstacles it is necessary to know what flows can be expected.

Figure 2-2 depicts a schematic illustration of the wind-flow pattern around a single rectangular building slab. Several wind flows can be distinguished and are explained below.

1. Approaching wind flow will stagnate at a certain point (65 – 75% of the building height according to Peterka et al. (1985)). The flow from this
The stagnation point is divided into the lower pressure zones; upward, sideward and downward. One of the configurations in this study has the opening height at this stagnation point height.

2. A stream will flow over the building and merge with the upward flow from the stagnation point.

3. The downward flow from the stagnation point will produce a standing vortex at the ground level, the so-called horseshoe vortex. This vortex will circulate in this zone and cause nuisance at pedestrian level.

4. The vortex in front of the building will attach to the corner streams and merge into a general flow around the corners. These flows also cause wind-nuisance at pedestrian level.

5. In the leeward zone of the building a backflow or recirculation flow occurs. It represents a low pressure zone and creates low rotating vortices behind the building.

6. At the leeward side of the building another stagnation zone occurs. At ground level, at the end of the recirculation zone, the wind speeds are low and the flow direction is opposite to the original wind direction.

7. The flow follows its initial direction, beyond the stagnation zone, with low wind speeds for a long distance.

This study will examine whether the upward flow from the stagnation point (1, Figure 2-2) and the flow at roof height (2, Figure 2-2) can be influenced by the design of the building. The height of wind turbine openings will be considered as well. The stagnation point height and the downward flow will be taken into account in the research. The two pressure systems are connected through the openings in the building. This can result in strong wind flows in these openings. The streamlined shape of the Strata tower and the sharp-edged roof may have an influence on the wind-flow pattern.

Please note that the surroundings of a building have a crucial influence on the wind flow results (Balduzzi et al., 2012). Unfortunately, due to time constraints, the surroundings are not explicitly modeled in this study.

2.2 Wind energy

Harvesting wind energy in the built environment depends mainly on the wind flow itself. Due to the complexity of wind flows in urban areas, innovative solutions should be found to convert wind energy into electricity. In certain cases innovative solutions are able to extract as much energy as possible from the complex flows because of the proper design of building and building arrangement.

2.2.1 Wind turbines, how do they work?

In order to make a wind turbine suitable for the built environment, it is necessary to gain knowledge on how a wind turbine operates in general. Wind will force the blades of a wind turbine to rotate, the rotating rotor is connected to the main shaft, which spins a generator to create electricity (Figure 2-3).

There are two types of aerodynamic interaction of the blades with the wind: drag and lift interaction. Drag devices (e.g. Savonius wind turbines) are not used in commercial wind turbines for producing electricity. These devices are inefficient and require more material than lift devices (Nelson, 2009). Lift devices
(e.g. Darrieus wind turbines) use airfoils for blades and use lift force to move faster than wind, which makes these devices more efficient in terms of aerodynamics. The tip speed ratio, the speed of the blade tip divided by wind speed, is a variable used for determining efficiency.

Note that a number of blades rotating slowly can extract as much energy as a single blade rotating fast.

### 2.2.2 Wind turbines in urban areas

Wind turbines can be integrated in the built environment in three main ways (Campbell & Stankovic, 2001):

- Stand-alone,
- Building mounted,
- Building augmented.

Stand-alone wind turbines are located on a free standing tower at a significant distant away from the building. Building mounted wind turbines are installed on the building structure. Building Augmented Wind Turbines (BAWTs) are installed at buildings where the building geometry is shaped to direct the wind flow towards the wind turbines.

High-rise buildings represent the largest potential for wind energy generation in the built environment. These building types obtain increased wind speeds and therefore increased wind energy potential due to the height and absence of constructional obstacles. The vicinity to electricity users and minor visual impact to the surroundings increase the potential for acceptance as wind energy harvesting in the built environment (Müller et al, 2009).

Complex turbulent wind flows are common around high-rise buildings, with separation, stagnation, and pressure zones (Cermak, 1976; Beranek & van Kooten, 1979; Stathopoulos, 2007). Streamlined buildings affect the flows around them, and if properly designed they can even increase the wind energy potential. The flows around such buildings can be less turbulent and without separations, which are important advantages. A downside of streamlined buildings is the limit in building factors (e.g. net internal area –NIA--; usable floor area -UFA). A trade-off must be made between wind energy performance and other design factors. The façade of a building has more wind energy potential than a roof according to Rao (2011). Rao (2011) explains that turbulence and separation occurs at areas of increased wind speeds concerning a bluff building. Optimizing the building shape can improve the feasibility of installing a wind energy system on a building roof or façade.
Besides different possible locations for wind turbines, different types of wind turbines are available. Below we describe wind turbines often applied in the built environment (Cace et al., 2007). Note that here we do not mention wind turbines for non-urban environments.

The horizontal axis wind turbine (HAWT) represents the propeller-type rotor mounted on a horizontal axis. This wind turbine needs to be positioned in the wind direction by means of a tail or active motorized yawing system. HAWTs are dependent on the wind direction and therefore highly sensitive to changes in wind direction and turbulence. These changes negatively affect the wind energy performance due to the repositioning of the wind turbine into the wind flow. The HAWT is most favorable in an open area with few obstacles.

![Figure 2-4. Horizontal Axis Wind Turbine (Symscane, 2015).](image)

The vertical axis wind turbine (VAWT) represents a vertical main rotor shaft with vertical blades attached to it. Small VAWTs are suitable to harvest wind energy from the urban environment. Their performance is independent of the wind direction.

![Figure 2-5. Vertical Axis Wind Turbine (solar conduit, 2015).](image)

Due to the overall lower efficiency of a VAWT – even though the fluctuations in wind directions have less negative effects –, a HAWT is commonly used in the built environment and in this study as well. Three 9 m diameter HAWTs are installed on the Strata tower. Several state-of-the-art solutions are described in the next section to improve the performance of this wind turbine.

### 2.2.3 Shrouded Wind Turbines

Micro-wind turbines, used in the built environment, are subject to several technical challenges. These challenges are comprised of large fluctuations in wind direction and wind speed, unpredictability of wind flow and its high turbulence (Kosasih & Tondelli, 2012). These challenges can be solved by applying a diffuser-augmented wind turbine (DAWT). A diffuser is added to the general HAWT. The power output of a wind turbine can be improved by increasing the mass flow rate through the opening and decreasing the wake rotation downstream of the turbine (Foreman et al., 1977).

A brim/ flange can be added to reduce the exit pressure that results in drawing more air through the turbine (Abe et al., 2005; Ohya et al., 2008). Figure 2-6 describes the cross section of a shrouded wind turbine and its elements.

![Figure 2-6. Schematic representation of shrouded wind turbines (Kosasih & Tondelli, 2012). Left; nozzle-diffuser wind turbine. Right; diffuser-brim wind turbine.](image)

According to Kosasih & Tondelli (2012), the performance of a DAWT is increased by approximately 60%. If a nozzle-diffuser is used, the performance can even be increased by 63%. Though the difference between a nozzle-diffuser and a sole...
diffuser augmented wind turbine is not significant, the nozzle provides more stable performance when wind direction is changed, in contrast to a sole diffuser.

2.2.4 Building Augmented Wind Turbines

Aside from the Strata tower, there are several buildings with integrated wind turbines. Several cases make use of streamlined buildings with so-called building augmented wind turbines. BAWTs are considered a relatively new kind of wind energy system. In the next sections several examples are provided.

Bahrain tower

The Bahrain World Trade Centre, completed in 2008, is a twin skyscraper complex. With a height of 140 m, this commercial building hosts three HAWTs. These turbines are arranged along the facade at 60 m, 98 m, and 136 m height supported by bridges linking the two towers together. The alignment of the buildings is explained by the prevailing wind direction from this angle. The wind flow from the Persian Gulf is accelerated by the passage between the two buildings. According to Killa & Smith (2008), the system should generate 1100 MWh/year to supply 11% of the building electricity demand.

Figure 2-7. Bahrain World Trade Centre (Jones, 2010).

Pearl River tower

The Pearl River tower, completed in 2011, is a 309 m high-rise building in Guangzhou, China. The tower incorporates four large openings of approximately 40 m² at levels 24 and 48. These openings serve as a pressure relief valve and are an ideal source for a wind energy system. The VAWTs should produce 40 MWh/year per opening and supply 1% of the total energy demand (Epstein, 2008).

Figure 2-8. Pearl tower (Liggett, 2010).

Project WEB

Project WEB is based on twin tower buildings with three HAWTs placed between them. Though being similar to the Bahrain tower, the project has put more effort in the encasing of the wind turbines. A prototype has been built for this building with one of the wind turbines to analyze the building shape aerodynamics (Campbell & Stankovic, 2001; Dutton et al., 2005).

Figure 2-9. Project WEB (Campbell & Stankovic, 2001).
**Strata tower**

For the case study in this research, several of the above ideas have been already incorporated in the design. Since the problem states that the geometry of the building is not optimized for the wind energy performance of a wind turbine, a design solution for the Strata tower could be a combination between a shrouded wind turbine and a building augmented wind turbine. The Strata tower is already considered as a streamlined building with augmented wind turbines due to the encasing of the wind turbines. Adapting the shape of the wind turbine encasing could improve the wind energy performance of existing wind turbines.

### 2.3 Wind and its energy potential

Though in this study the wind turbine performance is not assessed, it is necessary to know what the wind energy potential is dependent on.

Manwell et al. (2009) divides the wind power assessment into three steps: the meteorological potential, the site potential and the technical potential. The meteorological potential of a site can be calculated using data from nearby meteorological stations. To enhance the accuracy of the assessment, the Weibull distribution function of wind speed can be used (Savenkov, 2009; Ohunakin, 2012). The Weibull parameters $c$ and $k$ describe the wind distribution in combination with a cumulative exceeding probability function $P_e(U)$:

$$P_e(U) = A(\theta) \cdot \exp \left[ - \left( \frac{U}{c(\theta)} \right)^{k(\theta)} \right]$$  

($8$)

$P_e(U)$ - probability of exceeding of wind speed $U$ at meteorological site during wind direction $\theta$, $A(\theta)$, $c(\theta)$, $k(\theta)$ probability, velocity scale and shape parameters for wind direction $\theta$.

Site potential can be assessed with different research methods. Mathematical models are considered difficult to use and are time-consuming. In-situ measurements along with the determination of the efficiency of certain wind turbines before integrating them into an existing building, are very accurate (Abohela et al., 2013). However, this method is expensive and time-consuming. Wind tunnel measurements are considered reliable if the wind tunnel is an atmospheric boundary layer tunnel. Moreover, wind tunnel tests can be conducted only on scaled models of buildings, which can cause the Reynolds number to drop below the threshold for fully turbulent flow, predicting unreliable flows. CFD numerical modeling is less time-consuming and less expensive than the above-mentioned methods. However, CFD simulations are sensitive to the input of the user and they should be performed in combination with wind tunnel or in-situ measurements in order to validate the computational model.

Technical potential and energy estimation are calculated quantities based on the site potential and technical characteristics of wind turbines. Technical potential for instance, is based on the geographical potential reduced by the limitations imposed by the technical characteristics of a wind turbine. Though energy cannot be created or destroyed, it can only be converted to another form (Nelson, 2009), e.g. it is possible to convert the kinetic energy of the wind into electrical power. The energy of a wind flow passing through an area $A$ for a time period $t$ is:

$$E_k = P \cdot t$$  

($9$)

$E_k$ - energy of wind (J), $P$ - power (W/m$^2$), $t$ - time (s),

Where $P$ is defined as:

$$P = \frac{1}{2} \rho A v^3$$  

($10$)

$P$ - power (W/m$^2$), $\rho$ - air density (kg/m$^3$), $A$ - area (m$^2$), $v$ - velocity (m/s).

The fundamental equations can be applied to a singular wind turbine which will take the technical specifics of the wind turbine into account (Manwell et al. (2009)).
Thus, the technical potential is based on the site potential of wind resource and technical characteristics of applied wind turbine. The equation (11) shows the dependency of the power output of a wind turbine on a wind speed. The coefficient of performance is the ratio of the maximum power obtained by a turbine from the wind to the total power available in the wind. Betz’s law states that the maximum theoretical value of $C_p^T$ equals 59.3% of the total wind power. This data is often supplied by the manufacturers. For all wind turbines $C_p^T$ is defined as:

$$C_p^T = \frac{T \omega}{\frac{1}{2} \rho A U^3}$$  \hfill (12)

Note that, in equation (12) the turbine front area is the area of the rotor or diffuser exit area (Kosasih & Tondelli, 2012).

**2.4 CFD guidelines**

This section explains some main features of the guidelines used for this CFD study, as recommended by the Architectural Institute of Japan (Tominaga et al., 2008) and the COST research cooperation (Franke et al., 2004; Franke et al., 2007) for urban flows.

---

**Franke et al. (2007) provides a checklist for several steps to be made in order to perform a CFD simulation.**

- Choice of target variables;
- Choice of approximate equations describing the physics of the flow;
- Choice of geometrical representation of the obstacles;
- Choice of computational domain;
- Choice of boundary conditions;
- Choice of initial conditions;
- Choice of computational grid;
- Choice of time step size (for unsteady simulations);
- Choice of numerical approximations;
- Choice of iterative convergence criteria

**2.4.1 Target variables**

The target variables should be determined and described beforehand. These target variables should include the variables that represent the goals of the research and the variables that can be compared to corresponding experimental data.

**2.4.2 Approximate equations**

The physics of the flow can be described by several approximate equations that still ensure a reliable model and, therefore, accurate results. Turbulent flow is often modelled by the Navier-Stokes equations (Franke et al., 2007). Franke et al. (2007) describes three sets of equations for averaging the basic equations to render it numerically solvable. The turbulent flow scales are filtered out and substituted by turbulent closure to model the replaced scales.

From the three sets of described equations the steady Reynolds-Averaged Navier-Stokes (RANS) equations for continuity and momentum provide a statistically steady description of turbulent flow. These equations are used in this study to analyze the wind flow in a computational domain with different building geometries (Franke et al., 2004).
2.4.3 Geometrical representation of the obstacles

To reproduce the wind tunnel experiments of Rambøll Danmark A/S (2006), the aerodynamic performance of the Strata tower was numerically analyzed as a single building without geometrical representation of surrounding buildings. Nearby obstacles – trees and surrounding buildings - are considered of lesser importance and therefore, not added to the computational model.

2.4.4 Computational domain

The computational domain is dependent on the target area assigned for investigation. A single building requires a computational domain as described in Figure 2-10 with distance values extracted from Franke et al. (2007) and Tominaga et al., (2008). The vertical extension should be at least five times the building height. The distance is necessary to prevent artificial acceleration of the flow over the building due to the top boundary. Additional requirements for distance suggest its dependency on the blockage. The blockage is defined as the ratio of the projected area of the building in flow direction to the free cross section of the computational domain.

The lateral extension of the computational domain is defined by the required blockage and recommended distance of 5\(H_b\) between the building’s sidewalls and lateral boundaries.

The longitudinal extension of the computational domain consists of the area in front of the building (approach flow) and the area behind the building (wake). For the approach flow a distance of 5\(H_b\) is recommended, though some studies recommend a distance of 8\(H_b\) as mentioned in Franke et al. (2007). The region behind the building is limited by the outflow boundary. In case of a single building the distance from the building to the outflow boundary should be at least 15\(H_b\). This distance allows the flow to redevelop behind the wake region.

For validation studies with data from wind tunnel experiments, the computational domain should be adapted to the wind tunnel dimensions and scale of the tested model.

2.4.5 Boundary and initial conditions

The boundary conditions represent the influence of the surroundings that are cut off by the computational domain. At the inlet of the domain a vertical average wind profile and turbulence quantities should be assigned. These profiles depend on the roughness characteristics.

The roughness characteristics are imposed on the ground plane and wall surfaces of the building. These are comprised of the standard wall functions (Laudner & Spalding, 1974) with sand-grain based roughness modification (Cebeci & Bradshaw, 1977). The wall function modeling method will optimize computational

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_{top})</td>
<td>Roof of the building to top of computational domain</td>
<td>(\geq 5H_b)</td>
</tr>
<tr>
<td>(L_{ext})</td>
<td>Lateral extension between building side walls and lateral boundaries of computational domain</td>
<td>(\geq 5H_b)</td>
</tr>
<tr>
<td>(L_{in})</td>
<td>Distance between the inflow boundary and the building wall</td>
<td>(\geq 5H_b)</td>
</tr>
<tr>
<td>(L_{out})</td>
<td>Distance between the outflow boundary and the building wall</td>
<td>(\geq 15H_b)</td>
</tr>
</tbody>
</table>

Figure 2-10. Recommended domain extensions for computational domain. \(H_b\) is the building height of the Strata tower.
time and storage. This allows additional empirical data, such as wall roughness, to make the model more detailed. In order to correctly apply the wall roughness to represent the rough fetch upstream of the model, the equivalent sand-grain roughness height $k_s$ and the roughness constant $C_s$, should conform to their relationship with aerodynamic roughness length $y_0$. This relationship is described by Blocken et al. (2007) as follows:

$$ k_s = \frac{9.793y_0}{C_s} $$  \hspace{1cm} (13)

A careful representation of the flow near the ground surface is required for atmospheric boundary layer (ABL) flow in building simulation according to Blocken et al. (2007). Several requirements for upstream and downstream regions are set up to achieve horizontal homogeneity of the wind speed profile. These requirements include horizontal homogeneous ABL flow in the upstream and downstream regions of the domain on which the wall functions are imposed. Another requirement is the determination of the physical roughness height $k_r$ and the related aerodynamic roughness length $y_0$. The relationship $y_p > k_r$ must be met, where $y_p$ represents the distance from the center point $P$ of the wall-adjacent cell to the bottom of the domain. $k_r$ represents in this case the physical roughness height of the terrain.

According to Blocken et al. (2007), the vertical wind speed and turbulence profiles must be in equilibrium with the roughness characteristics of the ground surface in order to maintain horizontal homogeneity. There are several reasons for horizontal inhomogeneity to occur:

- Lack of compatibility between the shape of the imposed inlet profiles;
- Type of turbulence model;
- Wall functions;
- Other computational parameters.

Performing a simulation in an empty computational domain before conducting simulation with the building models present is advised by Blocken et al. (2007b).

### 2.4.6 Computational grid

Franke et al. (2007) and Tominaga et al. (2008) provide recommendations to avoid errors caused by the chosen configuration of computational grid. A building side/edge should contain at least 10 cells and the expansion ratio between two adjacent cells should be below 1.3.

To obtain the grid-independent solution a detailed grid-sensitivity analysis should be conducted. Results of a converged solution provided by three different meshes (fine – medium – coarse) should be compared between each other. As soon as two neighboring grids provide similar results a grid-independency is achieved (Franke et al., 2007).

### 2.4.7 Numerical approximations

Tominaga et al. (2008) states that first-order upwind schemes should not be used for numerical approximations. The large numerical viscosity causes diffusion of the spatial gradients of the flow quantities.

Franke et al. (2004) applies the first-order upwind schemes only in the initial iteration phase, after this initial set-up second-order schemes should be applied.

### 2.4.8 Iterative convergence criteria

Sufficient convergence should be achieved in order to keep the iteration-convergence error small. Termination of the simulation can only be done when the residuals for continuity, momentum, turbulent kinetic energy, and turbulence dissipation rate are sufficiently low and constant with increasing number of iterations (Franke et al., 2007). The residual value, for which the solution of each target variable will be considered converged, should be of at least five orders of magnitude. Overall, this type of convergence is achieved if the residuals are constant for approximately 1000 iterations.
3 Validation study

In order to obtain accurate results from CFD studies, it is necessary to validate the computational model by comparing CFD results with experimental data obtained by in situ measurements or wind tunnel experiments. In this case, the previously conducted studies by BDSP Partnership (2005), Rambøll Danmark A/S (2006) and, to a smaller extent, RWDI Anemos Consulting Engineers (2007) provide boundary conditions and results from their wind tunnel studies. This chapter describes the studies used for validation.

3.1 Study outline

BDSP Partnership (2005), Rambøll Danmark A/S (2006) and RWDI Anemos Consulting Engineers (2007) were commissioned to perform a study on feasibility of the building integrated wind turbines for the Strata building. Rambøll performed wind tunnel experiments and CFD studies to assess the wind potential of the Strata design. For both studies a simplified model of the Strata tower was used. Rambøll clearly mentioned the need for further studies on optimization of the opening shape.

For the wind tunnel study, a scale model of 1:180 was used. Note that this report will describe dimensions and values in full scale. The measured values are specified as the wind velocity amplification $\frac{U_n}{U_0}$, where $U_n$ is the wind speed (m/s) at a certain point inside the wind turbine opening and $U_0$ the reference wind speed at the same height but in a free field without buildings. No information was provided on the wind tunnel dimensions and used wind profiles. BDSP Partnership (2005) provided a wind profile for the urban terrain near the Strata tower (Appendix C - Figure 10-1). The measured mean speed profile is fitted by a power-law expression with $\alpha = 0.15$. The reference speed for the prevailing wind direction is 4.3 m/s at 10 meters height, the reference wind speed at 150 meters is 5.6 m/s for Heathrow Airport. A reference speed of 4.5 m/s at 50 meters height is used for a wind direction along the wind turbine openings at the Strata tower urban terrain during the validation study. The results reported in BDSP Partnership (2005) are limited to contour plots.

RWDI Anemos Consulting Engineers (2007) performed a wind tunnel study with the main focus on the mean pressures for ventilation design purposes. In this study a 1:300 model including surroundings was used. This study provided the pressure coefficients $C_p^T$ at different locations on the Strata tower facades.

$$C_p^T = \frac{p}{\frac{1}{2} \rho U_{ref}^2}$$

For the validation of the computational model used for evaluation of several design solutions of the Strata tower, the first two studies mentioned above have mainly been used.

The target variable in this study is the wind velocity distribution through an opening. The openings in this study represent the position in which the building integrated wind turbines are located at the top of the Strata tower. The dependency of the velocity on the shape of the openings, their height and the shape of the building will be analyzed.

3.1.1 Domain

The domain dimensions (W x D x H = 1500 x 3000 x 900 meters, Figure 3-1) are defined according to the CFD guidelines mentioned in section 2.3 since no
clear information on domain extensions is given by Rambøll and BDSP Partnership.

3.1.2 Boundary conditions

A wind speed profile is provided in BDSP Partnership (2005) (Appendix C - Figure 10-1). This profile is retrieved from meteorological data of Heathrow airport weather station. This wind profile together with $y_0 = 0.55$ m, the aerodynamic roughness length, obtained by fitting the wind profile with a log-law profile, are used in the computational model.

The turbulent kinetic energy per unit mass $k$ is calculated from the turbulence intensity $I_u$ that is measured during wind tunnel experiments. Tominaga et al. (2008) use $k = (I_u U)^3$ assuming that RMS values of velocity fluctuations $\sigma_v^2 = \sigma_w^2 \approx \sigma_u^2 / 2$. The turbulence dissipation rate $\varepsilon$ is defined as:

$$\varepsilon = \left(U_{ABL}^* / \kappa (y + y_0)\right)^3$$

where:
- $U_{ABL}^*$ - friction velocity (m/s),
- $\kappa$ - von Karman constant 0.42 (Richard & Hoxey, 1993),
- $y$ - height coordinate (m),
- $y_0$ - aerodynamic roughness length (m).

The sand-grain roughness height $k_s = 0.97$ m and roughness constant $C_s = 5.5$ for the ground surface are determined according to the requirement (13) mentioned in section 2.4.5. The first cell height of 1.5 m for the initial grid also fulfills the requirement of $y_p > k_s$.

Since a metal paneling is used in the construction of the Strata tower, $k_s = 0.005$ m and $C_s = 0.5$ have been used for the building surfaces. Behind the building a pressure outlet is assigned. The top and lateral boundaries of the domain are considered as symmetries (Franke et al., 2004).

3.1.3 Homogeneity analysis

In order to check the horizontal homogeneity of the wind speed profile along the domain, a simulation of the empty domain is performed. The profiles of mean speed, turbulent kinetic energy and turbulence dissipation rate are taken along the vertical line at the inlet of the domain and at the location of the building (Figure 3-3). The imposed computational settings and parameters can be found in Appendix C - Table 10-1.

Though no significant acceleration of wind speed near the ground surface is noticed, there is a decrease in turbulence kinetic energy. Therefore, the dependency $k = 3.33(U^*)^2$ is used in this study (Richards & Hoxey, 1993). The calculated profiles (Figure 3-4) show no significant deviations from the inlet profiles. Therefore, these boundary conditions are applicable for this validation study.
3.1.4 Grid-sensitivity analysis

A grid-sensitivity analysis is done for three grid configurations: a fine grid; 4.2 million cells, - a medium grid; 3.2 million cells, - and a coarse grid; 2.4 million cells (Figure 3-5). If a coarser grid provides similar results to a fine grid configuration, the configuration with less cells can be used in simulations to decrease the computational time.

The grid around the Strata tower is meshed in two steps. First, the body-fitted grid presented by van Hooff & Blocken (2010) is created. This grid is based on a pre-meshed 2D ground plain that is translated over vertical axis to avoid generation of undesirable pyramidal and tetrahedral cells. Second, the roof region is meshed. Unfortunately, due the complex roof shape of the Strata tower the use of tetrahedral cells cannot be entirely avoided here. In order to limit the inaccuracies caused by these type of cells, the quality of the grid is examined on the absence of skewed cells. This has been achieved by means of size functions in the pre-processor Gambit 2.4.6.

The results for the three simulated grid configurations are compared along the vertical lines at 10 meters in front of the building (Figure 3-6) and inside the center opening. In addition, a comparison is made along the horizontal line through the central opening.

Figure 3-3. Calculated profiles of mean wind speed, turbulent kinetic energy, and turbulence dissipation rate along the vertical lines of inlet and incident position.

Figure 3-4. Calculated profiles of mean wind speed, turbulent kinetic energy (constant at inlet), and turbulence dissipation rate along the vertical lines of inlet and incident position.
The region of interest lies inside the wind turbine openings. Therefore, an additional comparison is made along a vertical line inside the central opening and along a horizontal line through the opening.

The results (Figure 3-7) show similar values in the center of the line, though around the edges of the opening the values are different for the fine grid.

A grid convergence index study (GCI) has been carried out to estimate a discretization error for the grids. The GCI study will also show if the grid is refined enough through error estimation (Roache, 1994). Celik et al. (2008) provides a recommended procedure for estimation of the discretization error. The fine-grid convergence index is defined as follows:

$$GCI_{\text{fine}}^{21} = \frac{1.25e^{21}}{r^2 - 1}$$  \hspace{1cm} (16)

$e$ - approximate relative error (-), $r$ - grid refinement factor $>1.3$ (-).

The results shown in figure 3-9 provide the GCI for the fine grid. If the coarse grid results are situated inside the error area, the grids will comply with each other. As can be seen from figure 3-9 and Figure 3-10, the refinement of the grid configurations is considered to be appropriate.

As illustrated in Figure 3-6, the distributions of the mean wind speed and the turbulence quantities are very similar for all grid configurations. This would imply that a coarse grid has a similar accuracy as the fine grid.

Figure 3-6. Calculated profiles of mean wind speed, turbulent kinetic energy, and turbulence dissipation rate along the vertical line at 10 meters in front of the building.
Figure 3-7. Computed profiles of mean wind speed, turbulent kinetic energy, and turbulence dissipation rate along the horizontal line inside the central opening.

Figure 3-8. Computed profiles of mean wind speed, turbulent kinetic energy, and turbulence dissipation rate along the vertical line through central opening.

Figure 3-9. Grid Convergence Index for fine grid at the vertical line of the central opening.

Figure 3-10. Grid Convergence Index for fine grid at the horizontal line of the central opening.
3.1.5 Turbulence model

Rambøll Danmark A/S (2006) used SST $k$-$\omega$ turbulence model for their numerical study. It is common to use a $k$-$\varepsilon$ model or $k$-$\omega$ model in CFD research since they are proven to give reliable results (Letherman et al., 2000; Franke et al., 2004). A comparison is made between results obtained with the SST $k$-$\omega$ and the realizable $k$-$\varepsilon$ turbulence models.

Figure 3-11 illustrates the results provided by the both turbulence models. Though the mean wind speed profiles have similar distribution, a large difference in turbulence kinetic energy profiles is present. The overestimation of $k$ by the $k$-$\varepsilon$ model is in line with the well-known problem of this model (Tominaga et al., 2008).

The wind flow around the building and through the openings is solved by RANS equations in combination with the SST $k$-$\omega$ turbulence model. This combination of equations in this case is preferred to steady RANS in combination with a $k$-$\varepsilon$ turbulence model. The $k$-$\varepsilon$ is known to overestimate turbulent kinetic energy in stagnant flow regions (Franke et al., 2004), this issue was overcome by the developed SST $k$-$\omega$ model (Menter, 1997).

Since the openings represent ducts, the SST $k$-$\omega$ model is able to overcome the problem of the $k$-$\varepsilon$ model of overestimation of $k$ at the edges due to separation.

3.2 Results

Rambøll Danmark A/S (2006) provides a set of wind speed amplification factors at certain positions obtained by wind tunnel measurements. Figure 3-12 shows the positions of the measurement points used by Rambøll. In Figure 3-12 the results of the wind tunnel measurements with a scaled 1:180 model are compared to the results of CFD simulation.

Table 3-1. Wind speed amplification in intermediate points inside the wind turbine openings showing non-uniformity of wind velocity distribution

<table>
<thead>
<tr>
<th>Measurement points</th>
<th>Hole 1</th>
<th>Hole 2</th>
<th>Hole 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>U/U₀ (−)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.21</td>
<td>0.90</td>
<td>1.15</td>
</tr>
<tr>
<td>2</td>
<td>1.16</td>
<td>0.97</td>
<td>1.09</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>1.14</td>
<td>0.63</td>
</tr>
<tr>
<td>4</td>
<td>1.13</td>
<td>0.99</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Figure 3-11. Calculated profiles of mean wind speed, turbulent kinetic energy, and turbulence dissipation rate along the vertical line through central opening for both $k$-$\varepsilon$ and $k$-$\omega$ turbulence models.
The low values of the wind speed amplification factor inside the side openings at position 3 can be explained/ caused by the flow separation. Comparing the results from the CFD model created with the boundary conditions described before, the following can be noted:

- Though the results from the wind tunnel experiment show a higher wind speed inside the central opening (C2), the CFD findings of the side openings (C1, C3) are almost similar to the wind tunnel values (Figure 3-12).
- Overall, the wind distribution and flow separation inside the openings obtained by CFD simulations and wind tunnel experiments are similar (Table 3-1, 3-2 and Figure 3-13). Note that the results of Ramboll (2006) show a high wind speed amplification in the central point C2 but lower values in the intermediate points 1-4 in this central opening. Unlike that, the CFD results do show a similarity between the central point values and the intermediate point values. Also, the side openings (C1, C3) show higher wind speed amplifications than the central opening (C2).
3.3 Discussion

Though the wind distribution in central point C2 of the central opening and in the intermediate positions 1, 3 in the side openings, show a significant difference between experimental and CFD results, the remaining values do not deviate more than 10% from each other. The images in the report of Rambøll (2006) indicate a large blockage ratio of the wind tunnel, which exact value is not mentioned though. This could influence the accuracy of the wind tunnel experiments. Wind velocities are measured with two hot-wire x-probes of unknown manufacturer.

Note that, in case of the validation study the turbulent kinetic energy $k$ is changed into the relation $k = 3.33(u^*)^2$. This change results in a significant increase in turbulent kinetic energy that is imposed as inlet profile. This could result in discrepancies in the outcome as this case is considered a freestream and lower values of $k$ are more realistic. A higher imposed turbulent kinetic energy may lead to unrealistic values and non-convergence. However, the initial homogeneity along the domain shows a fair agreement in this validation study.

Since information provided about the wind tunnel experiments is insufficient, there could be different inaccuracies in the boundary conditions of the computational model that might influence the results. Overall, the experimental wind tunnel data and the CFD results show a fair agreement with each other.
4 Case study

During the case study the configurations described in section 1.4.3.1 are modelled in CFD and, the influence of the different design solutions on the wind speed distribution in the central opening is investigated.

4.1 The computational model

The different configurations are described in section 1.4.3.1 and illustrated in Appendix B - Table 9-1. These configurations are placed inside a domain following the guidelines described in section 3.1.1.

4.1.1 Numerical simulation parameters

This study was conducted with CFD simulations, using a pre-processor Gambit 2.4.6 and commercial code ANSYS Fluent 15.0 (ANSYS, Inc., 2009).

4.1.2 Computational geometry and grid

The domain of all studied configurations is defined according to the COST guidelines (Franke et al., 2007). The domain dimensions are W x D x H = 1500 m x 3000 m x 900 m. The simulations are performed in scale 1:180, as in the study of Rambøll Danmark A/S (2006). This chapter will report all dimensions and values in full scale.

Since the considered configurations just partially modify the initial building shape, the grid can remain the same in most of the domain. The medium grid is chosen as it provides the results similar to the fine grid and saves computational time compared to a fine grid configuration.

4.1.3 Boundary conditions

A mean wind speed profile and turbulence profile need to be imposed on the inlet of the computational model. A wind speed distribution for the urban area near the Strata tower is provided by BDSP Partnership (2005). The turbulent kinetic energy is determined by the relation $k = 3.33(u^*_{ABL})^2$. The turbulence dissipation rate is determined by the relation $\varepsilon = (u^*)^3 / \kappa(y + y_0)$.

Figure 4-1 shows the profiles for $y_0 = 0.5$ m imposed on the inlet of the domain. The building faces the wind so that wind direction is parallel to the building openings.

The boundary conditions imposed on the ground plane comply with the requirements stated in section 2.4: $C_s = 5.5$, $k_s = 1.0$ m and $y_0 = 0.5$ m. The side and top planes are considered symmetries and zero static pressure is imposed on the outlet.

During this study the influence of the wind direction, the shape of the openings, and the opening height on the wind distribution in the wind turbine openings is investigated.

4.1.4 Solver settings

The 3D steady RANS equations are solved with the SST $k-\omega$ turbulence model. The SIMPLE algorithm will solve the pressure-velocity relationship. Pressure spatial discretization is set to standard and second-order discretization schemes are used for the governing equations of convection and viscous terms. If no further reduction is shown for at least 1000 iterations, the solution is considered to be converged. The scaled residuals were below $10^{-5}$ for continuity, velocities, turbulent kinetic energy and turbulent dissipation rate.
4.1.5 Area of interest

The area of interest is the openings where the wind turbines are located. The wind potential inside these openings is evaluated by means of the wind speed amplification factor. The wind speed amplification factor is calculated for the central point of the three openings and as an average of the opening plane since the value at a single point might be deceiving. (Figure 4-2). The wind amplification through the opening, from inlet to outlet, is also examined to determine the importance of wind turbine placement inside the opening.

One remark needs to be made considering the description of inlet area and outlet area for different wind directions. Figure 4-3 shows the plane where the wind turbines are installed for both wind directions 0° and 180°.
4.2 Results

This section provides the results of the CFD simulations for the different configurations. The amplification factor $U_r/U_{ref}$ of the wind distribution is shown in several figures to determine if the wind distribution is dependent on the shape of the wind turbine openings and on the height at which the openings are placed.

4.2.1 Influence of the shape of wind turbine openings

The Strata tower provides an aesthetic appearance by integrating the wind turbines into the building. It has a remarkable roof shape, which results in a slope on the south side of the building. The shape of the wind turbines enclosures is influenced by this specific roof shape. This section will describe the results from the different design solutions for the wind turbine openings.

To compare the design solutions (Appendix B- Table 9-1; configuration 1a-c) with each other, firstly the base case is simulated. The design solutions shaped as a nozzle and a separate diffuser addition are then simulated and compared to the base case. Note that nozzle and diffuser are applied only to the central opening. Figure 4-4 depicts the results of these simulations as has been explained in section 3.2. Results are provided in Figure 4-4 for the three evaluation points positioned in the propeller plane for each of the three openings for a wind direction coming from $0^\circ$. The side openings ($H1, H3$) provide similar results for $0^\circ$ and $180^\circ$ wind directions due to the symmetry of the building. In general, the central opening ($H2$) shows a slight decrease in wind speed amplification factor comparing to the openings $H1$ and $H3$, except for the wind direction of $180^\circ$ (Figure 4-6).
Compared to the base case, the nozzle configuration shows significant increase in wind amplification factor for the actual building orientation and for the orientation to the prevailing wind direction of $0^\circ$ (Figure 4-4 - Figure 4-5). The diffuser configuration shows little to no improvements in wind amplification for these wind directions.

Note that there is almost no difference in wind amplification factors between actual and $0^\circ$ building orientation.

However, for the wind flow coming from the opposite direction of $180^\circ$ the significant increase in wind amplification is shown for all three cases (Figure 4-6). The design solution with the diffuser augmented wind turbine shows the largest increase of wind amplification compared to the base case.

Contour plots in Figure 4-7 and Figure 4-8 show the wind flow pattern in three sections of the computational domain. Top views of figure 4-7 show the high amplification values (in red) in the central opening of diffuser configuration for a wind direction of $180^\circ$. The low pressure wake behind the building (downstream part of the domain) is reduced compared to the wind direction of $0^\circ$. 
Figure 4-7. Velocity contour plots of Strata tower depicting the wind speed amplification for front, side and top view sections of the wind turbine openings with wind direction 0°.

Figure 4-8. Velocity contour plots of Strata tower depicting the wind speed amplification for front, side and top view sections of the wind turbine openings with wind direction 180°.
Figure 4-9 shows the flow separation occurring at the boundaries of the central opening for the three configurations. Sloped shape of the roof seems to have a positive effect for the wind amplification and flow uniformity for northern winds coming from direction of 180° (Figure 4-8, below). Also, less flow separation occurs at the upstream edge of the opening.

Figure 4-10 shows the contour plots of the wind speed amplification factor for the wind turbine openings in the plane where, currently, the central wind turbine is situated. This position is 1 meter from the opening inlet. In the case of the wind direction of 180°, the wind turbine is situated at 1 meter from the outlet. Note that, for all three cases, this plane corresponds to the plane where the wind turbine is situated in the base case (Figure 4-3).

The three images in the left column (Figure 4-10) show (from top to bottom) the velocities distribution for the basic, nozzle and diffuser configuration for a wind direction of 0°. The flow separation is visible in all three configurations and the distribution of the velocity over the plane is not uniform. This would mean improper boundary conditions for wind turbines affecting their performance.

The right column (Figure 4-10) shows velocities for the three configurations for a wind direction coming from 180°. Early flow separation can be seen for the basic configuration. The nozzle and diffuser applied to the central opening show their influence on the side openings, where the flow separation is enhanced. However, the amplification factors in the central opening, where the adaptations are applied, are significantly increased.

![Velocity contour plots: section through central opening viewed from the side for wind directions 0° (above) and 180° (below).](image)
Figure 4-10. Contour plots of wind speed amplification factor. Left; wind direction of 0°, plane taken at 1 meter from the opening inlet. Right; wind direction of 180°. Plane taken at 1 meter from outlet. Top to bottom; basic, nozzle and diffuser configuration.
4.2.2 Influence of opening height

The wind turbines on the Strata tower are placed at the top of the roof, at a height of 141 meters. Considering the basic wind flow around a building (Peterka et al. 1985) a large part of the wind flow will be blocked by the building and flow to different sides around the building, through a path with least resistance. We consider two additional heights to place the wind turbine openings: (1) the stagnation point, at approximately 70% of the total building height, and (2) lower level, since a large part of the flow is directed downwards from the stagnation point. Figure 4-11 - Figure 4-12 show the comparison between the placement heights and wind direction. The measurement points are taken at the central point of the openings. Note that, contrary to the results described in section 4.2.1, amplification factors are decreased for the wind flow coming from the 180° direction. This would mean that the sloped roof and building shape have a significant influence on the wind speed amplification factor.

An increase in wind speed amplification factor, compared to the standard configuration of the Strata tower, can be obtained by placing the openings at the stagnation height.

Figure 4-11. Wind amplification factors for openings at different placement heights and wind direction coming from 0°.

No significant difference is observed for the openings placed at lower level comparing to the standard configuration, the amplification factors seem to be similar to each other.

Figure 4-13 shows the velocity contour plots for configurations with the openings placed at different heights. $U_{\text{max}}$ shows no major deviations from the current base situation for wind direction of 0°. However, there is a decrease in velocities inside the opening for the configuration with the opening at a lower level with 180° wind direction. Note that the wind distribution through the opening is more uniform in case the openings are placed at stagnation height or at pedestrian level. This could be due to the longer distance from the inlet to the outlet of the duct.

Figure 4-12. Wind amplification factors for openings at different placement heights and wind direction coming from 180°.
4.2.3 Influence of building shape on the diffuser augmented wind turbine

The results from section 4.2.1 for the diffuser augmented wind turbine (DAWT) question its performance. As described in 2.2.3, a DAWT should have an increased power output. However, in the case of the Strata tower, the diffuser is located in the favorable wind direction but shows no significant increase in wind amplification. In fact, the DAWT shows even a decrease in wind speed amplification.

These results triggered an investigation on the influence of the building shape on the diffuser performance. A computational model is made with the same dimensions and computational settings as in the base case. However, the building has been removed from the domain in order to investigate only the diffuser aerodynamics.

Figure 4-14 shows the results for the two models: base case with DAWT and diffuser only, taken in the central opening H2. As can be seen, the performance of the diffuser is reversed by the building shape. The single diffuser shows higher amplification factor for the wind direction of 0°, however for building integrated diffuser the wind direction of 180° provides higher wind...
amplification inside the opening. Therefore, the diffuser is influenced by the presence of the building and in particular the building shape.

4.2.4 Influence of measurement positions on amplification factor

One of the shortcomings of the research from Rambøll Danmark A/S (2006) was insufficient information available for validation. The experimental data was available for certain measurement points in the model. During this study a comparison is made between point values and average values taken over a plane, a disc in the case of the openings (Figure 4-3; orange line depicts the position of the plane). Appendix D, Figure 11-1 to Figure 11-3 show the results of this comparison. Though the average values are lower – the separation flow around the edges is taken into account – the trend, compared to the point values, is similar.

4.2.5 Influence of the position of the wind turbine in the passage

The position of the wind turbines is different for every opening due to the geometry of the building. The curve of the south wall provides an increased distance from the wind turbine to the inlet for the side openings (1.2 meters) compared to the central opening (1 meter - Figure 4-15).

The CFD models make it possible to identify the position of highest amplification factor inside the opening. For an optimal wind turbine performance a uniform wind flow field is advantageous. Figure 4-16 shows a distribution of the wind amplification factors along the central horizontal axis of the opening. For the current situation and assuming the prevailing wind direction to be 0°, the optimum position for the wind turbine would be a distance of 3 – 5 meters from the inlet area to reach $U_{\text{max}}$. This implies that the maximum wind speed amplification factor is reached outside the building structure. Figure 4-17 depicts the wind flow amplification factor if the wind flow comes from 180°. This figure shows a more steady flow through the central passage. It also shows that the optimum of the amplification factor can be achieved by positioning the wind turbine at a distance of 0 – 2 meters from the outlet area.

As Figure 4-9 shows, $U_{\text{max}}$ values are located in the regions with flow separation. Therefore, placing a wind turbine at the $U_{\text{max}}$ position will not automatically provide the optimal performance of the wind turbine as the uniformity through the plane is not guaranteed.
Figure 4-16. Wind speed amplification factor for the three design solutions along central horizontal line through central opening, wind direction 0°. Inlet area positioned at \( x = 0 \).

Figure 4-17. Wind speed amplification factor for the three design solutions along central horizontal line through central opening, wind direction 180°. Outlet area positioned at \( x = 0 \).
5 Discussion

5.1 Design solutions

5.1.1 Influence of opening shapes

Three configurations and two design solutions for the shape of the wind turbine opening are investigated in this study. The results for the basic configuration reveal the shortcomings of the current design. The two proposed design solutions consider adding a nozzle to the wind turbine inlet area, and a diffuser to the wind turbine outlet area. These configurations have all been tested for three wind angles of attack, 0°, 15° and 180°. For both 0° and 15° the results for the two design solutions were similar to the base case and showed negligible improvements. No significant increase in wind speed amplification factor was noticed. This does conclude that for the current situation of the Strata tower, the difference of 15° with the prevailing wind direction for London will not significantly influence the wind energy performance.

Both design solutions, where the nozzle and diffuser are applied, do show a significant increase of wind amplification factor compared to the basic configuration when the wind angle of attack is 180°. The implementation of a diffuser shows the largest increase in amplification factor.

Separation of the approach flow occurs in all configurations and for each wind angle. It is however limited in the configuration with nozzle implementation for the wind direction of 180°.

For an optimized wind energy performance of a wind turbine, a uniform flow field should be provided at the propeller plane. Due to the separation flow in all configurations the non-uniformity is present in almost all cases. In case of the wind angle of 180° and the two design solutions, an increase in uniformity is visible (Figure 4-10). Note that the planes are taken at 1 meter from the outlet area, where currently the wind turbine is situated in the completed Strata tower. Some discrepancies are visible for the diffuser augmented configuration. The most promising solution seems to be to rotate the wind turbine 180° and add a nozzle to the opening. By most promising solution we mean a high amplification factor as well as a uniform flow field. Another, more drastic though the outcome similar to the above, solution would be to rotate the building by 180°.

5.1.2 Influence of opening height

Three configurations considering the placement height of the wind turbine openings are modeled. The basic configuration represents the Strata tower in its current appearance. The second configuration locates the openings at 70% of the building height, at the stagnation point. The final configuration locates the openings at pedestrian level. From the results it can be concluded that the maximum wind speed amplification occurs for the central opening of the building with the openings at the stagnation point. Overall, the flow for the wind turbine openings placed at stagnation height show a more stable behavior due to the longer passage through the building. Separation occurs at the edges where the approach flow enters the opening, and the long distance to the outlet provides sufficient space to reattach (Figure 4-13). The wind openings at 10% of the building height, just above pedestrian level, cause wind-nuisance at this level. The low pressure zone at the leeward side of the building enhances a recirculation flow with high wind speeds compared to the regular recirculation zone behind a building with no openings. Furthermore, this height will most likely be influenced by surrounding objects that are not modeled in this study.
5.1.3 Influence of the building shape on the DAWT

Results from the diffuser configuration with wind angle 180° show a large increase in wind speed amplification. This contradicts the general idea of a shrouded wind turbine (Foreman et al., 1977). To investigate if this phenomenon is caused by the specific roof shape of the Strata tower, the diffuser as used in the Strata tower model, is simulated without the building. The results depicted in Figure 5-1 show the positive influence of the diffuser being enhanced by the building shape.

5.2 Current limitations of the study

The limitations of this project are summarized before stating the conclusions in the next chapter.

- This study is limited to a specific case study of the Strata tower;
- Though several previously conducted studies have been performed, there was limited data available to validate the computational model for this numerical study;
- Due to time constraints no explicit surrounding buildings or vegetation was modeled. Therefore, the influence of the urban environment surrounding the Strata tower was not taken into account. However, the aerodynamic roughness length corresponding to the urban area was applied in the computational model;
- The wind turbines situated in the Strata tower have a fixed yaw. The efficiency of the wind turbines is assumed to be constant and independent on the angle of wind direction. If a wind turbine was installed with the possibility to rotate to the oncoming wind, the results might have been different. Note that, non-perpendicular angles of attack create a skewed wake in the downside of the rotor. This phenomenon affects the wind energy system performance (Manwell et al., 2009);
- Since this case study is executed with a HAWT, only these wind energy systems were taken into account in assessment of the design solutions.

Figure 5-1. Vector plots of wind velocity amplification factor through basic configuration (left) and diffuser without building (right) for wind angle 180°.
5.3 Recommendations for further research

Recommendations for further research are specific to this case study of the Strata tower:
- Conduct research with an extensive representation of the surroundings for this specific location.
- Perform a feasibility study on different types of wind turbine systems installed in the openings.
- Perform a study on the diffuser design solution, where the diffuser walls have a range of material roughness quantities.

Recommendations for further research in general comprise:
- Perform generic study on the energy potential of single, small high-rise buildings with integrated wind turbines. Set up specific guidelines regarding ideal height of openings, influence of roof shape, and influence of different wind turbine systems.
- Conduct the extensive study on the optimization of a shrouded wind turbine for integration in high-rise buildings, as it has potential if placed correctly.
6 Conclusions

6.1 Design solutions

Changing the shape of the openings to create a shrouded wind turbine has the largest influence on the amplification factor when the wind flows from a 180° angle.

6.2 Placement height for the openings

Changing the height of the openings and wind turbines would affect the wind energy potential in case of placing the openings at the stagnation point. It slightly affects the amplification factor if the wind would flow from the opposite direction (180°) in the central position of the opening. Lowering the position of the openings does not significantly influence the wind potential for the prevailing wind direction. A decrease in amplification factor, if the wind flows from the opposite direction, is noted while changing the height of the openings to a lower level. Adapting the placement height to the stagnation point and lower level would generate a steadier flow through the opening due to the longer duct. This could have a positive effect on the wind turbine performance and in case of the stagnation point placement height the positive effect is shown in Figure 4-13.

6.3 Position of the wind turbine

The wind turbine is currently positioned at 1 meter distance from the inlet area. Considering the current situation, this would imply that an amplification factor for the central wind turbine can be achieved of 1.0 or lower. This condition applies to all design solutions proposed. If the wind would flow from the opposite direction (180°), a steadier flow throughout the entire passage is achieved, and therefore, the amplification factor is increased in general. By that, the wind turbine would be positioned at the highest amplification factor, ranging from 1.15 – 1.30 per design solution.

6.4 Influence of the building shape on the DAWT

The roof shape of the Strata tower strongly influences the performance of the diffuser augmented wind turbine solution. In case of a different roof shape the results might have been different.

6.5 Overall conclusions

- The positioning of the Strata tower along the prevailing wind direction axis, differing by a 15° angle, has no influence on the amplification factor of the wind flow through the openings and should therefore, have little to no effect on the wind turbine performance.
- In the current situation with a rotated wind turbine, the wind turbine position should be anywhere from 0 – 2 meters from the outlet area. This would provide the highest amplification factor.
- Note that, in case of adopting the design solutions, separation flow at the edges should be taken into account. This is the least for the wind turbine with nozzle design solution.
- The most effective solution would be to add a diffuser augmented wind turbine to the Strata tower. The downside of this is the effect it has on the wind flow approaching the side openings and hence, the wind turbine performance in these openings.
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Figure 1-7; Meteorological Office UK; website: http://www.metoffice.gov.uk/climate/uk/regional-climates/so; data retrieved 25-2-2014.

Figure 1-8; Rambøll Danmark A/S (2006); page 8.

Figure 2-3; Renewable Energy Hub; website: https://www.renewableenergyhub.co.uk/how-a-wind-turbine-works.html; data retrieved 15-1-2015.

Figure 2-4; Symscape; website: http://www.symscape.com/blog/anatomy_horizontal_wind_turbine; data retrieved; 31-1-2015.

Figure 2-5; website: https://solarconduit.com/shop/wind/urban-green-energy-vawt-uge5mc10m.html; retrieved: 31-1-2015.


Figure 2-8; website: http://inhabitat.com/worlds-greenest-skyscraper-pearl-river-tower-almost-complete/; data retrieved: 31-1-2015.

Figure 2-9; CORDIS; website: http://cordis.europa.eu/result/rcn/80425_en.html; data retrieved: 31-1-2015.

Figure 8-1 - Figure 8-5; Curtesy of BFLS Architects. Flanagan Lawrence, 66 Porchester Road, London W2 6ET, United Kingdom

Figure 10-1; BDSP Partnership, 2005; Castle House, Wind Turbine Study. Appendix C, p.1.
Figure 8-1. Impression of Strata tower seen from north-east direction.
Figure 8.2. Side view, front view (north-east), and front view (south-west) of the Strata tower.
Figure 8-3. Floor plan 37th floor.

Figure 8-4. Front view and side view of the integrated wind turbines roof of the Strata tower.
Figure 8-5. 3D impression of roof structure with integrated wind turbines.
## Appendix B

Table 9-1. Overview of investigated design solutions based on placement height (1-3) of wind turbine openings, shape (1a-c, 2, 3) of wind turbine openings, and effect of the diffuser without the building present (4).

<table>
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<th>2</th>
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<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
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<tr>
<td>c</td>
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<table>
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<th>1</th>
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<tbody>
<tr>
<td>H = 141 m</td>
<td>H = 104 m</td>
<td>H = 15 m</td>
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10 Appendix C

![Wind profiles for London Heathrow and Strata tower (Castle house) for the prevailing wind direction (BDSP Partnership, 2005)](image)

**Figure 10-1.** Wind profiles for London Heathrow and Strata tower (Castle house) for the prevailing wind direction (BDSP Partnership, 2005)

**Table 10-1.** Computational settings and boundaries used in the validation and case study.

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<th>Fine</th>
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<tr>
<td>Model scale</td>
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<tr>
<td>$H$ [m]</td>
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<td>$D$ [m]</td>
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11 Appendix D

Figure 11-1. Wind amplification factors for all configurations for wind directions 0 degrees. Left; evaluation points H1 – H3. Right; evaluation plane average value.

Figure 11-2. Wind amplification factors for all configurations for wind directions 15 degrees. Left; evaluation points H1 – H3. Right; evaluation plane average value.

Figure 11-3. Wind amplification factors for all configurations for wind directions 180 degrees. Left; evaluation points H1 – H3. Right; evaluation plane average value.