Master’s Thesis Proposal

The Virtual Wind Tunnel as a Design Tool

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Faculty of Civil Engineering and Geosciences

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# Table of Contents

Table of Contents .................................................................................................................................. 2

1. Introduction ....................................................................................................................................... 3

2. Background Information .................................................................................................................. 5
   2.1 Theoretical backgrounds ............................................................................................................... 5
       2.1.1 Velocity profile, internal boundary layer and roughness of the surface ............................................... 5
       2.1.2 Wind around buildings .............................................................................................................. 6
   2.2 Wind tunnel VS CFD-models ....................................................................................................... 7
       2.2.1 Wind tunnel tests ....................................................................................................................... 7
       2.2.2 CFD-models ............................................................................................................................. 8
       2.2.3 Evaluation .................................................................................................................................. 9
   2.3 CAD Models ................................................................................................................................... 10
   2.4 Object Orientated Models ........................................................................................................... 10
   2.5 Geographic Information System ................................................................................................. 11

3. Research description ....................................................................................................................... 12
   3.1 Problem definition ....................................................................................................................... 12
   3.2 Research goal .............................................................................................................................. 12

4. Project approach ............................................................................................................................. 13
   4.1 Literature Study ........................................................................................................................... 13
   4.2 Getting acquainted with CFD-Software ....................................................................................... 13
   4.3 Uniting CAD-, GIS- and Object Orientated data ......................................................................... 13
   4.4 Simplification of complex shapes ............................................................................................... 14
   4.5 Testing the method ...................................................................................................................... 14
   4.6 Final reporting ............................................................................................................................. 14

5. Table of Contents Final Report ...................................................................................................... 15

6. Time schedule ............................................................................................................................... 16

7. Graduation Committee ................................................................................................................... 17

8. Contact information student .......................................................................................................... 18

9. References ....................................................................................................................................... 19
1. Introduction

At the design stage of high rise buildings, there was in the past hardly any attention for wind loads. Because of the very large dead weight of these structures, wind loads did not have a significant effect on the structure. From the 1950’s, new and stronger materials were introduced in building engineering, which meant that the structures became lighter and smaller. As a consequence of this, wind loads have become more important for the engineering of high rise buildings. This has led to more research into wind loads on buildings, which finally resulted in different design rules for wind loads. Also the shape of buildings has become more important. The first high rise buildings had a more or less rectangular shape, but nowadays very much different and complex shapes are possible and/or required.

For the simple shapes of the first high rise buildings, the early design rules to determine the wind loads were sufficient. Because of the more complex shapes of buildings nowadays, it is no longer possible to determine the wind loads with the existing rules. Wind tunnel tests have been introduced to predict the airflow around buildings. With these tests, it is also possible to determine the wind loads on buildings for complex shapes. Disadvantages of these tests are the costs and the very large preparation time. Because of this, wind tunnel tests are not enough flexible as a design tool.
To obtain insight in the wind loads in the early stage of the design process, it has been suggested to use CFD (Computational Fluid Dynamics) as a tool to determine the wind loads. CFD forms an alternative for the expensive and time consuming wind tunnel tests. At Delft University of Technology a computational wind tunnel for the early design phases has been proposed, named ‘The Virtual Wind Tunnel’ (Van Nalta, [2]). The accuracy of an analysis application is not needed; the goal is an application which can be used during the design process to indicate the wind loads. The results of these indications can be used to optimize the design, which will result in a more efficient shape or a better structure.

Because the airflow around buildings is very much dependent of its surroundings, it is also desired to simulate the surroundings in the CFD-software. In a Geographic Information System, geographic data about the surface of the Netherlands and objects on that surface can be stored. When it is possible to unite the GIS-data for a certain location with data from design drawings of a building, a model in which the building and its surroundings are integrated can be created. Untill now, the surroundings are hardly taken into account in computer simulations. With these new models, a more realistic analysis can be made for air flows and wind loads on a building. In this way, a more accurate design tool will be gained.

Until now, CFD-software is still not capable to determine the wind loads on a building accurately, compared to wind tunnel tests. But, several investigations are done at the moment to improve the software, what makes it hopefully suitable as a design tool soon.

However, the input of a building design is still too complex. Building models, especially Object Orientated models (Tolman et al, [3]), contain lots of information which are not relevant for the simulation, but increases the calculation time tremendously. So, the input of the models must be simplified to make it suitable for use with CFD-software.
2. Background Information

2.1 Theoretical backgrounds

2.1.1 Velocity profile, internal boundary layer and roughness of the surface

The atmosphere is the layer around the earth which exists out of gasses. The thickness of the atmosphere is a couple of thousands kilometers, but most of the air can be found in the lower layer; the mass decreases with increasing height. The lower layer of the atmosphere, the troposphere, has a thickness of 13 kilometers. In this layer, 90% of the mass of gasses in the atmosphere can be found. Air flows in the atmosphere are a result of differences in air pressure. Air flow takes place from places with a high air pressure to places with a low pressure.

At great heights above the ground, air can move freely because of differences in air pressure. Near the ground, the airflow is slowed down by the surface. This happens for grown and built surfaces, as well as for open surfaces. The slowing down of the airflow is strongest directly above the surface and is decreasing with increasing height. In Figure 2.1, the average air velocity with increasing height (Velocity Profile) is given. An obstacle on the surface influences the profile, which is also shown in Figure 2.2.

Because of the roughness of the surface, turbulence is largest at low height. With increasing height, the turbulence is decreasing. Hence, the turbulence profile differs from the velocity profile. The thickness of the layer in which the airflow is influenced by the roughness of the surface and by the weather, is called the Atmospheric Boundary Layer (ABL). (Cauberg, [1]). Above a water surface the ABL is small; above a big city the ABL is large. In a small ABL, the airspeed at ground level will be higher than in a large ABL. See Figure 2.2.

By changing the roughness of the surface, the velocity profile and the thickness of the boundary layer will set up after a certain distance. For every change of the roughness, an internal boundary layer will develop, in which the airflow will adapt gradually to the new roughness of the surface (see Figure 2.3).
2.1.2 *Wind around buildings*

For wind above a municipal area, the airflow is strongly influenced by the existence of buildings. Such an obstacle in the atmospheric boundary layer results in a very complicated flow pattern. The incoming airflow must flow over and around the building, which leads to a very complex and turbulent pattern, also at pedestrian level.

If air flows perpendicular to a rectangular building, at 2/3 of the height a stagnation point will arise. Above this point, air flows up, and below this point, air flows down. At pedestrian level a whirl will arise at the front of the building, which flows to the building corners. Because at the corners also air comes down, the amount of air just above pedestrian level which has to be discharged to the corners will be larger. As a consequence, air velocities are increasing. In such an area, a lot of wind hindrance will occur. At the front of the building, an area will develop with relatively high pressure. At the back of the building, an area will develop with relatively low pressure. The air velocity at the back of the building is mostly low.

![Figure 2.4: Airflow around a building (Cauberg, [1]).](image)

The higher the buildings become, the more wind they will catch. At the top of such a building, a light swing can be felt in a huge storm. This is unpleasant for working at great height, but it is even more unpleasant for living there. The wind loads on a building have consequences for the safety and usability of buildings. It is in particular the stiffness of a building which determines the way in which a building can swing by hard wind.

High rise buildings also have a significant influence on wind behavior at pedestrian level. Because the wind must find another path, air velocities can become very high at pedestrian level, which results in passer-by’s not be able anymore to walk or cycle normally. Tests in wind tunnels or with the aid of computer models can prevent dangerous situations in such a case.
2.2 Wind tunnel VS CFD-models

2.2.1 Wind tunnel tests

With the growing complexity of building shapes, there is no certainty if the existing design rules to
determine the wind loads on a building approach reality. Because of this, more wind tunnel tests are
performed to predict the airflow around buildings. With these tests it is also possible for complex
shapes to determine the wind loads on a building.

For research in the wind tunnel it is important to choose the right boundary layer. (Internet, [1]). The
distance in which the surroundings is taken into account, is also important. The wind velocity profile
namely is influenced by the roughness of the surface over 5 kilometers upstream the building. Because
the roughness of the surface in front of the building is mostly not equal for all wind directions, an
arithmetic correction must be made for the influence of the different surface roughness.

Besides, the scale of the model for the wind tunnel test must be determined. Regularly the scale differs
from 1:200 until 1:400. The projected surfaces of the buildings are limited in relation with the
dimensions of the wind tunnel. Otherwise too much air will be blocked. The profile of the tested
objects may be 5% of the tunnel profile at maximum. If this blockade grade becomes too high, the
measured velocities will differ too much and a correction of the results must be made.

To obtain a smooth airflow around the model in the wind tunnel, the Reynolds number must be equal.
The Reynolds number is given by:

\[ R_e = \frac{v \cdot l}{\nu} \]

In which: \( R_e \) = Reynolds number \( l \) = length \( v \) = velocity \( \nu \) = kinematical viscosity

With a model at scale 1:250, the air velocity in the tunnel should be 250 times larger as in reality. With
a strong turbulent flow, the ‘Reynolds sensitivity’ will be strongly reduced, wherefore it is accepted to
work with smaller Reynolds numbers in the wind tunnel. In practice, airflow is often supercritical
\( (R_e > 3 \times 10^6) \), while in the wind tunnel airflow is subcritical. Only with round buildings and strongly
rounded building corners, the airflow resistance is strongly dependant of the Reynolds number. In such
a situation, the airflow at model scale can release at a different location from the building than in
reality. Therefore the measured airflow at pedestrian level can differ from the reality.

![Figure 2.5: Model in a wind tunnel](image)
2.2.2 CFD-models

CFD stands for Computational Fluid Dynamics and is the process of finding numerical solutions for flow equations. (Internet, [5]). Nowadays, CFD is used in many disciplines in the design process. Applications vary from determining the aerodynamics for airplanes and cars until calculating the heat development in buildings. In theory, the influence of wind around buildings can also be calculated with CFD-models. But, existing CFD-software has to be developed further to do this accurately. Until now, the expensive wind tunnel tests still give better results. If the existing CFD-software is improved, it will form a good alternative. For analyzing and visualizing this definitively offers specific advantages.

In CFD-models, a computer model is made of the urban environment and the design of a building. In fact, this is a numerical model. This model, also known as a mesh, consists of a large amount of volume cells. In these cells, the so called ‘Navier-Stokes’ equations are set up, whereby the way the air flows is defined. After fitting up the boundary conditions and attaching some properties to the various elements, the airflow can be simulated.

For simulating with CFD-models, very powerful computers are required. With these machines, calculation time can significantly be reduced and results are gained earlier. By applying some changes in the model, the designer quickly gets the consequences for the wind loads. In this way, CFD forms a powerful tool in the design process.

However, there are some disadvantages of working with CFD-models. The designer must have a thoroughly knowledge of fluent dynamics for determining the right parameters of the model. Besides, the amount of data after a CFD-simulation is huge. Results are not always clear.

![Figure 2.6: CFD-simulation airflow](image)
2.2.3 Evaluation

Wind tunnel tests and simulations with CFD-models are two different methods to determine the effects of wind on a certain object. Each method has advantages and disadvantages, which will be discussed in this paragraph.

Limitations

For simulating fluids with CFD-models or wind tunnel tests, a model of the reality is made. For wind tunnel tests, the model must satisfy some modeling rules. In a wind tunnel, whirls release at a different location from rounded buildings than in reality. This is caused by the small Reynolds number which is used in wind tunnel tests. Therefore, results of tests with round buildings or rounded corners are not representative. Simulations with CFD-models don’t have these restrictions, because scaling doesn’t take place. An important condition therefore is that the curved surfaces are correctly modeled. Another aspect is ‘blocking’ in the wind tunnel. The section of the model in a closed wind tunnel is 5% of the profile of the wind tunnel at maximum. With these scales, effects of little details on a specific shape can not be studied. In this case, CFD-models are more adequate.

Visualization

For the visualization of streams in wind tunnel tests, usage is made of smoke or fibers. With thermistors, the average wind velocities can be determined in a certain measure point. Before this, the representative measure points need to be defined in an accomplished way. To determine other quantities during a wind tunnel test, usage can be made of smoke or fibers to determine the flow direction, heat wires to visualize turbulence and pressure receivers to determine the pressure on a structure.

When using CFD-software, visualization of pressures, velocities and turbulence is possible in every arbitrary surface. Besides, it is even possible to release air particles in every arbitrary point and follow the procession of it. In this way, insight is gained in the consistency and structure of the airflow.

Results

With wind tunnel tests, measurements can be done relatively fast for all wind directions. Using CFD-models, a huge amount of calculations must be performed for every wind direction. This takes a lot of time. Wind tunnel tests are preferred when a lot of wind directions must be analyzed, whereby restricted measure points are sufficient. If detailed information is desired with a limited amount of wind directions, CFD-models are preferred. However, preparation of wind tunnel tests takes much more time and money than CFD-models. This is an important disadvantage of wind tunnel tests.

By using CFD-models, all aspects of the whole fluid field are determined. In every arbitrary point the velocity, fluid direction, turbulence and pressure can be defined. This is an important advantage of using CFD-models in stead of wind tunnel tests. Selection of the most critical places takes place by investigation of the simulation results. These places can’t be neglected. With wind tunnel tests, the model can’t be filled fully with sensors. So before the test, the most critical places must be defined. If the results of a wind tunnel test give rise to further analyses, new measures must be performed. This is not the case with CFD-models.
Conclusion

In the past, wind tunnel tests were the most suitable tool for designers to determine wind velocities and wind forces on complex buildings. Nevertheless, this method is far from perfect. Wind tunnel tests are influenced by scaling effects, which causes errors. Besides, wind tunnel tests are expensive and very time consuming, which make them unfit for a design tool. However, it can be very useful to get insight in airflows and pressures in an early stage of the design process.

Simulations with CFD-models are an accurate alternative for wind tunnel tests. Using CFD-models, very complex shapes can be calculated. Besides, in every arbitrary point of the model the velocity and pressure can be determined. Because simulations with CFD-models are also cheaper and less time consuming than wind tunnel tests, they are very suitable as a design tool.

2.3 CAD Models

CAD stands for Computer Aided Design and is the use of a wide range of computer-based tools that assist engineers, architects and designers in their design activities. (Internet, [3]). CAD is used in various disciplines, such as architecture, mechanics and engineering. There is a difference between 2D systems and 3D systems. The 2D systems are used for technical drawings and ground plans. 3D systems work with wire-, surface-, volume- or solid-models and are used for graphically representations or Object Orientated models.

First commercial applications of CAD were in automotive and aerospace industry. As computers became more affordable, the application area gradually expanded. CAD implementations have evolved dramatically since then. First, CAD was limited to producing drawings similar to hand-drafted drawings. Advances in computer technology have allowed more skillful applications of computers in design activities. Today CAD is not limited to drafting and rendering; it ventures into more intellectual areas of designer’s expertise.

2.4 Object Orientated Models

Information modeling is a modeling technology in which a model of the reality is described in terms of classes and its relations. In this context, a building model is a semantic description of an existing or new building, where the essential building characteristics are maintained. (Tolman et al, [2]). A semantic building model is built up of objects which are used in reality, such as wall, column, girder and space. The model contains essential characteristics of all these objects, but also information about the relations between these objects. An advantage of this is that the several objects have sense for the computer; the building model is interpretable for the computer.

Above mentioned building models are also known as Object Orientated Models. The real world is described in objects which communicate with each other. If, for example, a wall is replaced in the model, the windows, channels and sockets are also automatically replaced. This is very useful in the design process.

Contrary to object orientated models, CAD models have no sense for the computer. These drawings contain lines and points, but the interpretation is done by man. Object orientated models contain no lines or points; they are built up of walls, columns and girders. The interpretation is done by man and computer.
2.5 Geographic Information System

Geography is information about the surface of the earth and objects which can be found on this surface. (Internet, [2]). A Geographic Information System (GIS) is an information system with which data of such objects can be saved, edited and analyzed. Examples of real objects are roads, houses and channels. Virtual objects which can be used in a GIS are for example administrative area classifications and destinations. GIS links information, such as address data, with location. Quite often, data first has to be edited before it can be used in a GIS. Scanned maps or air views have to be transferred to the used reference system. Regularly, data has to be matched with a geographic position or a geographic object.

For the Netherlands, 2D geographic information about the surface and objects on that surface is stored in so called Top10 and GBKN (Grootschalige Basiskaart Nederland) models. (Internet, [6]). Besides, a database exists where the height of the surface and almost all objects in the Netherlands is stored. This database is called the AHN (Algemeen Hoogtebestand Nederland). (Internet, [7]). When this data is united with data from for example the Top 10 model, a 3D GIS model for a certain area can be created. As a research, this is done in the past for a part of the University of Delft district. The purpose of this research has been a high level of accuracy of the several heights. Still another method has to be developed to unite the 2D GIS models and the AHN database in a faster way. Only then it would be appropriate for use in the virtual wind tunnel project.

For consumers, application of GIS occurs mostly in route planners: by means of a postal code, the shortest or fastest route between two locations can automatically be determined. Weather maps are also well-known examples of the usage of a geographic information system.

For professional applications, GIS is mostly used in planning and for analyses of traffic, transport, environment and safety. Information of geographic objects can be linked with each other and analyzed. The connection is made by geographic objects which are registered by coordinates. For example, lots of organizations have an address database with several data connected to it. By representing this data, interesting information can be visualized.

Governmental institutions and public utilities use GIS to update the location of several utilities. Commercial concerns use GIS to unite customer data with demographic data and results of market research, to fit their market strategy. Finally, GIS is also used for military applications. Here, GIS is a tool for the preparation and accomplishment of a military operation.
3. Research description

In this chapter, a description is given of the problem that will be considered during the Master’s Thesis and the goals for the end result are set.

3.1 Problem definition

With the growing complexity of building shapes, the existing design rules to determine the wind loads are not sufficient anymore. Wind tunnel tests are a good alternative, but they take a lot of time and are very expensive. In the early design stage, hardly any use can be made of wind tunnel tests. But, in this stage of the design process, very important design decisions are made. More insight in wind loads and airflows around a building is desired in this stage of the design process.

From aerodynamics, software is developed with which many fluids can be modeled. These CFD-models could also be used to determine the wind loads on a building and the airflow at pedestrian level. In this way, insight is gained in various quantities in a relatively short period.

Because airflow around a building is strongly dependant of the surroundings, it is desired to absorb the surroundings in the model. In a Geographic Information System, geographic data about the surface of the Netherlands and objects on that surface is stored. When this data is united with data of a building design, a model is created with which the wind loads and airflows can be determined in a more accurate way. Here a problem arises, because data from CAD-models, Object Orientated models and GIS-models can’t be transferred one-on-one to CFD-software; it is very difficult to converge this data. Besides, CAD-models and Object Orientated models contain a lot of information that is of no use for the CFD-software and has to be filtered out. Small details of the design, such as door handles and railings, are also not very relevant to determine the wind loads and airflows, but cause a long calculation time. A method must be developed to reduce the amount of calculations, for instance by simplifying the building design and geometry of the surroundings.

Above mentioned leads to the following problem definition:

‘Wind tunnel tests to determine the impact of wind around a building are not suitable for use in the early design process. CFD-software forms a good alternative, but data from CAD-models, Object Orientated models and GIS-models can’t be transferred one-on-one to CFD-software. Besides, without simplification of the input, the calculation time is much too long.’

3.2 Research goal

The goal of this Master’s Thesis is to develop a method with which data from CAD-models, Object Orientated models and GIS-models can be united to one model which can be used by CFD-software to determine the wind loads on a building. To limit the calculation time of the CFD-software, the model has to be simplified by reducing the input of the building design and the surroundings.
4. Project approach

To accomplish the research goal, the research will be divided in several steps. In this chapter, these steps will be discussed.

4.1 Literature Study

To obtain more knowledge about geometry, CAD, Object Orientated Models, GIS, CFD and wind engineering, a literature study will be done to the various subjects. The gained knowledge can be used during the rest of the research.

Product: Report of the gained knowledge  
Duration: 7 weeks  
Study points: 8

4.2 Getting acquainted with CFD-Software

Because I will work a lot with CFD-software during my Master’s Thesis, a thoroughly knowledge of this software must be gained. Because the package ‘Fluent’ is available at the Delft University of Technology, I will work with this package. Especially Gambit and T-grid, the Fluent pre-processors, will be studied. Gambit and T-grid are the programs used to set up the base geometry and boundaries of the problem in 2D and 3D, and they generate the grid or mesh for the CFD solver Fluent. The way Gambit and T-grid work and how they generate the grids and meshes shall be studied.

Product: Report of the gained knowledge  
Duration: 5 weeks  
Study points: 6

4.3 Uniting CAD-, GIS- and Object Orientated data

To determine the wind loads on a building with CFD-software, a method must be developed to unite CAD-, GIS- and Object Orientated data. In the first place the CAD-package Rhinoceros will be used to unite the several models. This will first be done for simple building shapes, later more complex building models will be used to unite CAD- and GIS-data. Another method to unite data from several models is the use of a Database Management System (DBMS). Also this method will be studied, whereupon the best method can be determined.

However, there is still no appropriate method to develop a 3D GIS model from 2D models and the AHN database. Nevertheless, to unite 3D building models with a GIS model, the existing 3D GIS model of the University of Delft district will be used.

Product: Method to unite data; explanation in a report  
Duration: 9 weeks  
Study points: 11
4.4 Simplification of complex shapes

The model of the building and its surroundings has to be simplified before it is imported in the CFD-software. Otherwise the model is far too complex, what can lead to a long calculation period and a huge amount of data. In what extent a change in geometry will affect the airflow and wind loads, shall be studied. Besides, the way in which the model of a building can be simplified shall be investigated. Balconies, railings and door handles cause a long calculation time, but are not relevant to determine the wind loads. By applying a certain roughness to the façade for example, the effect of these objects can be charged without modeling them separately.

Product: Method to simplify the model of a building and its surroundings; explanation in a report
Duration: 8 weeks
Study points: 9

4.5 Testing the method

The developed method to unite data from CAD-models, Object Orientated models and GIS-models has to be tested. An investigation will be done if the model can be imported in the CFD-software. Besides, the accuracy of the results before and after simplification of the model and the consequences of the simplification for the calculation time will be investigated.

Product: Review of the developed method; report of the test results and accuracy of the method
Duration: 4 weeks
Study points: 5

4.6 Final reporting

At the end of the research, the results will be presented in a final report, a final oral presentation and a poster.

Product: Report, final presentation
Duration: 3 weeks
Study points: 3
5. Table of Contents Final Report

Preface
Summary
1. Introduction
2. Research description
3. Wind Engineering
4. Computational Fluid Dynamics
5. CAD, GIS and Object Orientated Models
6. Uniting CAD- en GIS-data
7. Simplification of complex shapes
8. Review of the developed methods
9. Conclusions and recommendations

References
Appendices
6. Time schedule

- **6. Proposal**
  - Establish contacts
  - Write proposal
  - Distribute Master's Thesis Proposal

- **1. Literature Investigation**
  - CAD / Geometry / GIS
  - Wind Engineering
  - CFD models

- **2. Getting acquainted with CFD**
  - Learning OpenFOAM, T-grid and Fluent
  - Generation of grids / meshes
  - Distribute first report

- **3. Unitizing CAD and GIS data**
  - Recap
  - No lab
  - Database Management System
  - Distribute second report

- **4. Simplification of Complex Shapes**
  - Investigation in simplification
  - Apply methods for simplification
  - Study the effects of change in geometry

- **5. Testing the Method**
  - Import in CFD-software / adjustments
  - Accuracy of results

- **6. Final Report**
  - Reporting
  - Finishing Final Report

- **7. Presentation**
  - Presentations
7. Graduation Committee

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9. References


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