Faculty of Environmental Sciences

Modeling of wind passing through a city and optimal places for urban wind turbines

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Supervised by:

Satoshi Takahama,

Julie Varupenne, Quentin Pointdextre & Paul Giard

Written by:

Solal Luisoni & Alexandre Schlatter

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1 Introduction

1.1 Situation

In Switzerland, most electric energy sources are renewable. They come mostly from hydraulic power activities. However, wind turbines doesn't have the same popularity as dams. This can be explained. Classic wind turbines are really big, noisy and they need a strong wind to generate electricity. They are a great renewable source of energy but they are hard to implement. They need a lot of authorizations and they usually cause a lot of complaints from the neighbors, because of the noise or just the visual pollution. They also need to be placed in a very open area where there is no obstacle, usually a large field or even offshore. They are therefore located far from the cities and the electricity has to be transported long distances to be used.

1.2 Introducing urban wind turbines

An alternative is to use urban wind turbines. They are smaller, quieter and they need less wind to function. It can be a good solution for implementing wind turbines in an urban environment. This project aims to analyze the possibility of having wind turbines in our cities. We have chosen the Savonius wind turbines for our model, as they seem to be the best choice for our needs. They can take wind coming from everywhere, they function even with a wind going as low as 2 [m/s] and they are quiet. This is the perfect combination for an urban use.

Figure 1: Wind turbines at Jinguashi by Fred Hsu, 2010, CC Licenses CC BY-SA 4.0.

2 Method

2.1 Deviation from the project proposal

The main topic of this project was to model the wind in the city of Lausanne and determine the energy produced from wind turbines placed at strategic locations. First, we wanted to model a city map and determine the roof surface. Then we wanted to find where the wind is the fastest and find its location to evaluate the power produced to see if urban wind turbines are a sustainable solution for the future. The first issue we encountered was that we could not find data of a wind field for a surface. We also did not find the data needed to make a model of every building in Lausanne. Even if we could, the modeling would have probably been to complex and difficult for us and for a regular computer to run. We made the decision to create an imaginary city starting with a squared flat map. On this map, we added a few buildings where the wind can not pass. Using the *Navier-Stokes*

Equation we were able to see the behavior of the wind. This equation was our main problem because both of us never took the fluid mechanic course. We had to rely on the code of others in order to properly use the equation and have satisfying results.

2.2 Approach

In order to see how the wind would react in a city, we needed to know how winds evolve in an area. *The Navier-Stokes Equation* describes the conservation of momentum in fluid for a controlled volume. It evaluate each points in the plot according to backward, forward and sides conditions to know the direction and velocity of the wind in every point. This equation is written down as follow:

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = \nu \nabla^2 \vec{v} - \frac{\nabla p}{\rho} + F$$

Where:

- $\vec{v}$: the velocity
- $\nu = 1.608 * 10^{-5}$ $[m^2/s]$: the kinematic viscosity
- $\rho = 1.184$ $[kg/m^3]$: the density
- ∇p : the gradient of pressure
- $F = 1$: the driving force

The Navier-Stokes Equation can only be approximated, so we had to simplify the solution assuming we were in closed system with continuous surface. We also made some assumptions that the fluid is a Newtonian fluid, the density is constant which means it is not compressible and we also fixed the temperature at 25[°c].

We wanted our project to represent the most cities possible. This is why the size, the shape and the location of every building is defined randomly each time we run the code. We assumed that the wind only comes from the left of the plot and left the plot on the right, because as we can imagine for a city, the wind only travel in between the buildings and does not go back in the streets after browsing the city. On the same note, we assumed that the wind is much bigger than the city. This means that the wind is not really impacted as a whole, and thus, the angle at which the wind arrives is the same as when it leaves.

As the wind approaches a building, we made sure it will not go through and will pass around it. The program iterates on himself, updating the map so the wind field can stabilize himself according to the buildings that could be around. After that, the program finds the locations where the speed is the fastest and then calculates the power that the wind turbines produce in those places.

The power formula (see below) represents the potential power a turbine can produce depending on the wind velocity. C_p represents the coefficient of power in general between 0.35 and 0.45. A is the area of wind swept by the pales of the turbine. A typical Savonius wind turbine will have a 400 [mm] x 400 [mm] cross-section area, representing 0.16 m^2. The formula for the wind power is the following:

$$\frac{1}{2} * Yield * \rho * A * v^3 * C_p$$

Where:

- $Yield = 0.35$: Yield of Savonius turbines
- $\rho = 1.184$ [kg/m^3]: the density
- v : the velocity
- $c_p = 0.35$: Power coefficient
- $A = 0.16$ [m^2]: Area of Savonius turbines

We first did a model of a map acting as a two-dimensional channel flow without obstacle (*cf. Figure 2*). The wind then travels from east to west in a straight line, with no interference. We then added obstacles as area where velocity is zero. Putting conditions on the wind allowed us to see its path, where the wind was the strongest and where it decreased. The *Figure 3* shows the same channel flow but this time it has a building in the center so the wind has to go around it.

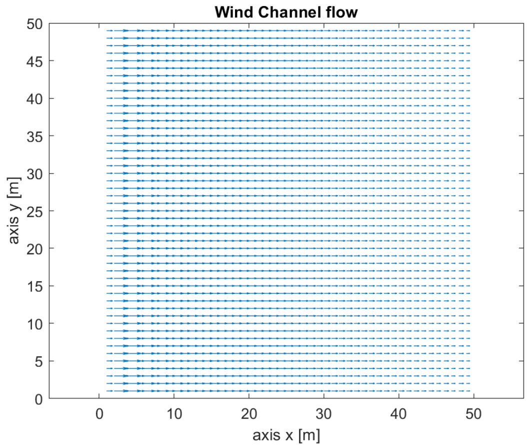

Figure 2: Representation of a theoretical channel flow.

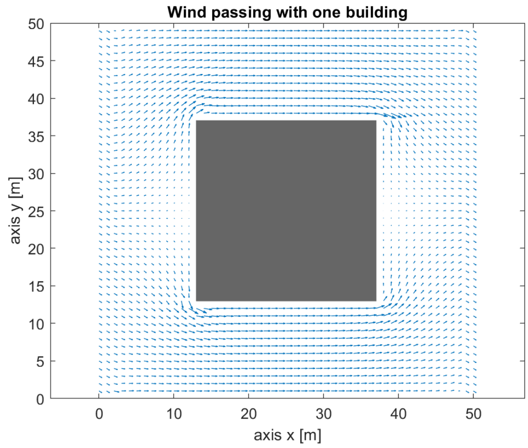

Figure 3: Behavior of the wind near a single building.

2.3 Choice of the programming languages

We decided to use the language C for the initialization of the map with the randomly placed buildings. We also used C for calculating the mean wind speed of the data from Lausanne and the power outputs of the wind turbines because C is really efficient for calculations. For Navier Stokes and the final graph, we decided to use Matlab as it is powerful for manipulating matrix. We didn't use C for the *Navier Stokes* solver, because it was a much more difficult work with the matrix, although the calculation would be faster.

3 Results

3.1 Outputs

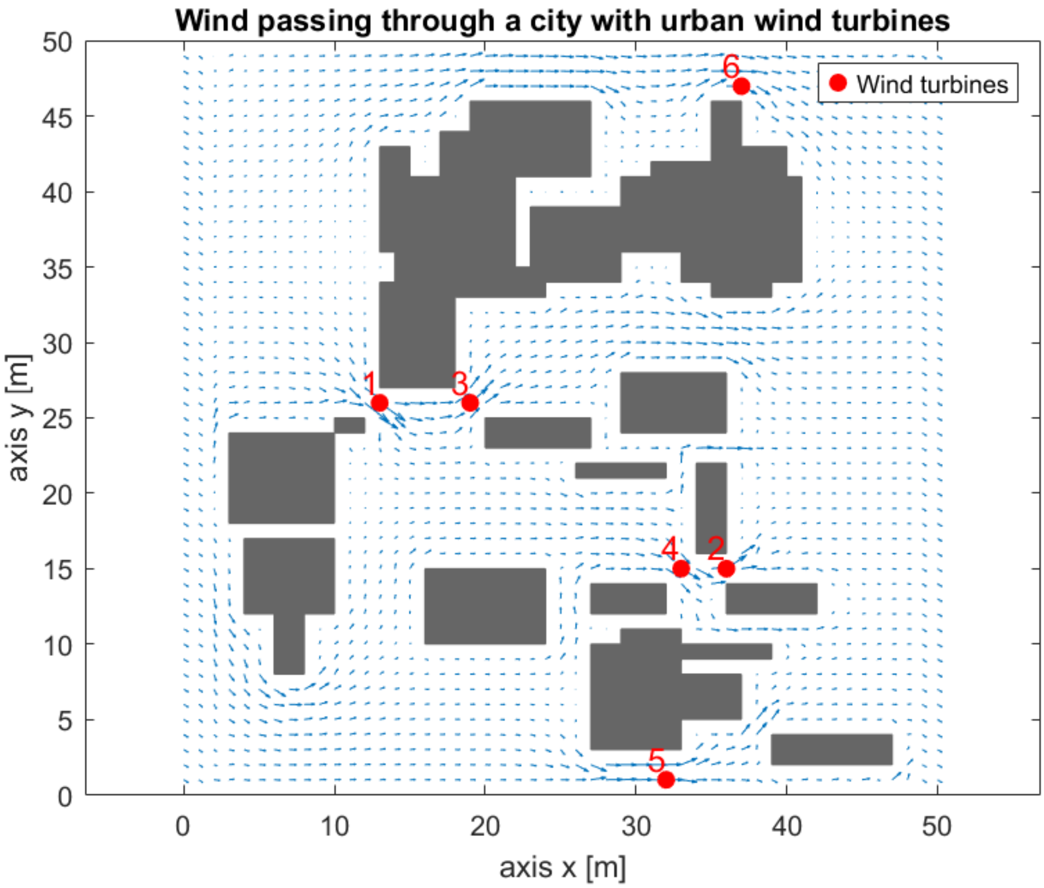

Figure 4: Modeling of the wind passing trough a city with buildings

Turbine	Coord X	Coord Y	Speed of the wind [m/s]	Power [kW]
1	14	27	7.34	4.08
2	37	16	5.71	1.91
3	20	27	5.43	10.27
4	34	16	5.14	1.64
5	33	2	4.07	0.69
6	38	48	4.04	0.68

Table 1: List of the wind turbines installed according to *Figure 3*

3.2 Discussion of the results

We made our model to generate random sized buildings and random repartition of the buildings over the map to be more representative of a real city. The map represents a city of 50 [m] x 50 [m] with 30 buildings. The buildings can overlay to make more interesting and real shapes. In *Figure 4* for example, there is only 13 buildings in the end. In this city, we wanted to implement 6 urban wind turbines where the wind was the strongest, with the condition that they cannot be next to one another. The map shows how the wind acts when it encounters buildings. We can see that there is some sort of funnel where a lot of wind passes. It is interesting to note that the wind passing through the different funnels has a greater velocity than everywhere else, especially than the velocity at the beginning of the city.

Coming back to the classic wind turbines, we said that they needed to be placed somewhere with no obstacle in order to capture the most wind possible, without any reduction of the velocity. It greatly reduces the optimal places for installing wind turbines. This is one of the reasons why wind electricity is so rarely used in Switzerland. However, there seems to be a solution. With our model of a city, we have discovered that we can use these obstacles in our favor. The key concept is the wind funnels. With smart placement, we can actually capture a stronger wind inside a city rather than outside it. In *Figure 4*, the wind arrives at a velocity of 1.28 [m/s] and leaves the city at the same velocity. However, during its time through the different buildings, its velocity varies with the location. According to *Table 1*, the wind where the first turbine is installed reaches 7.34 [m/s]. This shows the potential of using obstacles to increase the wind.

Using the information we got for the Savonius turbines and with the equation for the power, we have estimated that turbine 1 could have a production of roughly 4 [kW]. This power is enough to sustain approximately 5 to 8 households.

3.3 Limits of the model

There is limitations to our model. For one, we can only have a wind going from left to right. Because of it, we cannot have a model of a city with a wind coming from more than one direction, wich is why we had to calculate the mean direction of the wind in Lausanne and stick to this value for the modeling of our city. In the real world, the wind does not comes from only one direction and it most certainly is not constant in time and place. The calculation for the power of the wind turbine is simplified and does not take counts of some parameters. Another limitation of this project is the lack of the third dimension. Of course this would make the code a lot more complicated, but it would also make it more representative of a real city by allowing a fraction of the wind to go above the buildings.

3.4 Outlooks

If we had to continue working on this project, we would probably begin to implement the third dimension to the map. This alone will improve the precision of the results. We also want to return to our first desire of modeling Lausanne. With the right data, we can be able to make a good estimation of how the wind acts when traveling through Lausanne. This will make our project a great tool if the city of Lausanne ever wants to develop its renewable energy and implements urban wind turbines in its streets.

4 Conclusion

Throughout this project, we saw the behavior of wind, from a perfect channel flow to a city filled with complex buildings. As we could imagine, the wind flows in a straight line when it encounters no obstacle. In contrast, wind crossing a city will makes deviations and almost always create one or more wind funnels. The key point to remember is the fact that in those funnels, the wind tends to gain a lot of speed. During a small period, it can reach multiple times its initial speed. We can make use of this result by strategically placing wind turbines in those places, and thus, enjoy a stronger wind even in less windy areas. This can be a great opportunity for a small country like Switzerland where there is not a lot of places for classic wind turbines. Savonius wind turbines is a great alternative that takes advantage of the city architecture to install the turbines where the wind is the strongest.

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