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DESIGN OF THE CITADEL OF BONIFACIO URBAN AREA THROUGH EXPERIMENTAL AND NUMERICAL ASSESSMENT OF PEDESTRIAN COMFORT

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INTRODUCTION

The city of Bonifacio, located at the extreme south end of Corsica Island, is said to be the windiest city of Europe, and has earned its nickname as “The daughter of The Wind”. The Montlaur Citadel is a district of Bonifacio located on a small peninsula. It is an ancient military facility composed of various massive barracks and churches. The peninsula is characterized by its high cliffs (60 m above the sea level) which make the Citadel particularly exposed to high wind.
The city of Bonifacio is eager to modernize the location with various services and recreational activities. Urbalterre, an urban architect agency, was in charge of designing the urban area of the future Montlaur Citadel. Aware of the pedestrian comfort issues which may arise from the high wind blowing over the peninsula, Urbalterre wished to design the buildings sizes and locations in the district in order to optimize the pedestrian comfort on the citadel.

To do so, Urbalterre used a mix of numerical and experimental approaches to assess pedestrian comfort using:

- -Wind tunnel measurements based on Particle Image Velocimetry for a precise assessment of the wind behavior in the district
- -CFD simulations to optimize the design of the district, most particularly using vegetation

The study was conducted following 4 consecutives steps:
1) Assessment of the statistics of the wind blowing on the Citadel using CFD simulations to extrapolate weather data form a neighbor weather station to the location of the Citadel
2) A first precise assessment of the pedestrian comfort on an early design of the district using PIV measurement in a wind tunnel experiment
3) Successive iterations, using CFD, of the design of the district to enhance the pedestrian wind comfort
4) A final assessment of the pedestrian comfort in wind tunnel of the optimal version of the district.

Many previous studies presented methodologies for the assessment of pedestrian comfort [1][2][3]. The specificity of the present study is to combine PIV measurements in wind tunnel (very few experiments were presented to our knowledge) and CFD simulations carried out by the urban architect themselves thanks to the Urbawind software to optimize the design of the Citadel.

CALCULATION OF THE WIND STATISTICS AT THE CITADEL OF MONTLAUR

Weather data is available in the weather Station of Cap-Pertusato, located only 3km at the South East of the Bonifacio peninsula. It could be close enough to consider the weather data relevant to the one at Bonifacio. However, considering the high cliffs and the shape of the coast between Cap-Pertusato and Bonifacio, as well as the particular shape of the Peninsula, wind could be channeled by the topography. It was then preferred to use CFD to take into account the orography and roughness effect of the wind blowing between Bonifacio and Cap Pertusato.

To do so CFD simulations were carried out on a computational domain of 20km per 10 km as presented in Figure 1. The orography was taken into account in the CFD mesh with various resolutions, from 10 m on the peninsula till 200 m at the farthest locations of the Peninsula and of Cape Pertusato. Roughness was model as an input for the wall boundary conditions for the CFD code. Special attention was brought to the mesh with a boundary layer mesh generated all the other the terrain model with a first cell size of 2 m.

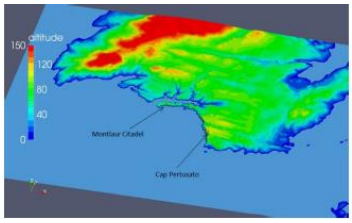


Figure 1 - Computational domain

Simulations were run with the ANSYS Fluent CFD software using a stationary Reynolds Average Navier Stokes approach combined with a k-Epsilon model. The so-called Beljaars formulation of the k-epsilon model was used to represent the behavior of the wind over the terrain.

Simulations were conducted for 18 wind directions (20° step). For each simulation, the wind "measured" 10 m above the ground at the Montlaur citadel was compared to the one "measured" at the weather station. Those simulations are not here detailed as it is not the main topic of the present paper. Figure 2 presents the flow topology and the wind speed 10 m above the peninsula for one wind directions.

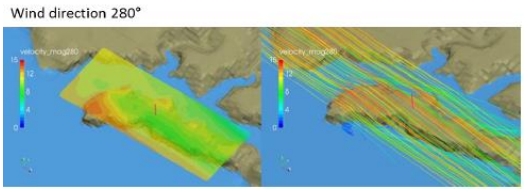


Figure 2 – Left: wind speed at 10 m above the peninsula; right: stream lines of the flow

Simulations allowed the weather data form Cap Pertusato station to be transferred at the location of the project. Statistics are then computed directly from the "corrected data". Figure 3 presents the wind rose obtained at the citadel locations. One can see that this wind rose is quite uncommon as the majority of wind events are concentrated along two wind directions, 280° and 60°. This is due to the particular location of Bonifacio at the extreme south end of the Corsica Island.

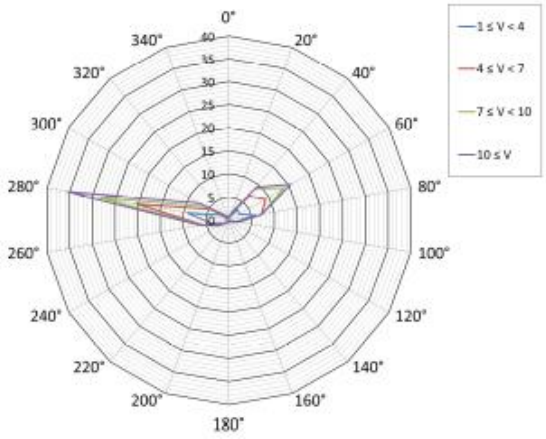


Figure 3 - Wind rose computed at the Montlaur District, wind speeds in m/s and frequency in %

Wind statistics are then modeled using Weibull functions for each wind direction written as:

$$P_i(X) = P_{Di} \exp\left[-\left(\frac{X}{A_i}\right)^{k_i}\right]$$

With the probability P_{Di} of the wind blowing along direction i and A_i and K_i the "shape" parameters of the Weibull function computed for every direction i. $P_i(X)$ is the probability that the wind exceed value X for wind direction i.
Urbalterre transferred wind rose thanks to CFD software for complex terrain called Topowind. Results from Topowind are similar from Fluent.

ASSESSMENT OF PEDESTRIAN CONFIGURATION IN THE INITIAL CONFIGURATION

A first design of the Montlaur district was proposed by Urbalterre and is presented Figure 4. Grey buildings are already built and need to be renovated without changing their shape. Red buildings are the new ones to be constructed. Those buildings are quite massive and may cause wind accelerations between them which might lead to pedestrian discomfort.
This first version is then tested in wind tunnel using a 1:100 scale model

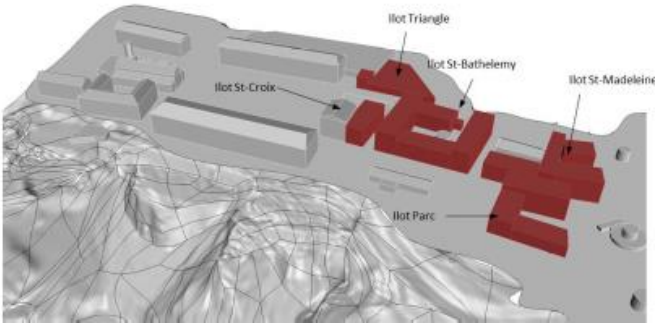


Figure 4 - First version of the district

Wind Tunnel setup

Experiments were conducted in the NSA (stands for Nouvelle Soufflerie Atmosphérique) Atmospheric Boundary Layer Wind Tunnel of the CSTB (Centre Scientifique et Technique du Batiment) located in Nantes France. This wind tunnel is equipped this a very long test section which allow a boundary layer profile to be generated owing to appropriate roughnesses set up upstream the model. A schematic of the wind tunnel is presented Figure 5.

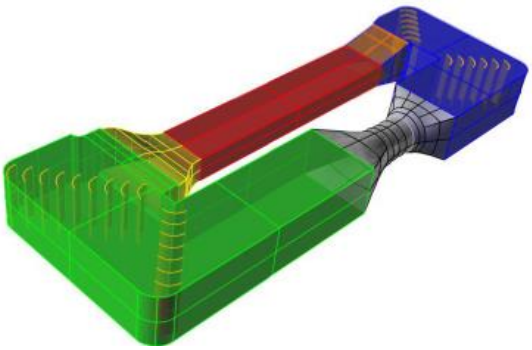


Figure 5 - NSA Wind tunnel at CSTB

A 1/100th model of the Montlaur citadel was created. The cliffs of the Peninsula were represented with large pieces of foam machined. Buildings were constructed using Plexiglas for the wall, wood and foam for the roofs. A picture of the models is presented Figure 6.

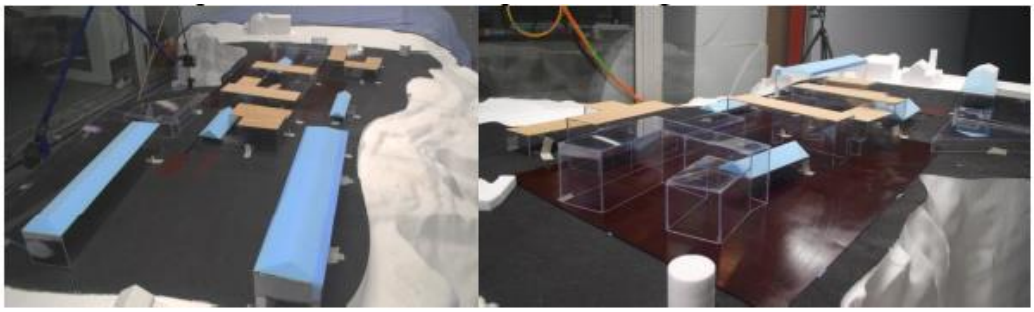


Figure 6 - Model of the district for wind tunnel experiments

Figure 7 presents the boundary layer profile generated in the wind tunnel. This profile is relevant to the one occurring on the sea (roughness 0 according to Eurocode regulation). The picture also represents a cross section of the district located ether at sea level (in red), or on top of the peninsula (in blue). One can see that it is necessary to represent the peninsula as it will have a major impact on the way the wind will impact the buildings.

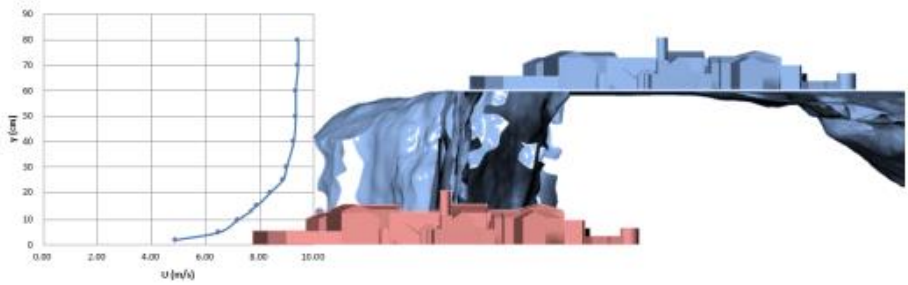


Figure 7 - Boundary layer profile in the wind tunnel

Additional velocity profiles were measured on the top of the peninsula model without the buildings. The velocity measured at 10m full scale (10cm model scale) above the ground will be used as the reference wind speed to extrapolate wind statistics which have been previously computed. Figure 8 plots the wind speed and turbulence intensity profiles measured on the top of the peninsula model. The mean wind speed at pedestrian level (1.5cm model scale) is 6.3 m/s with 28% of turbulence; and 8.8m/s with 21% turbulence at 10m above the ground.

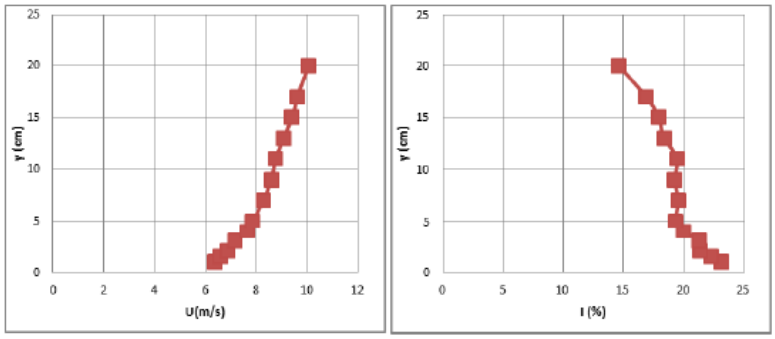


Figure 8 - Velocity profile on the peninsula model, left: mean wind speed, right: turbulence intensity

PIV Measurements

A 2D2C (2dimensions 2 components) PIV System was used in order to measure the velocity a pedestrian level. A picture of the setup is presented Figure 9

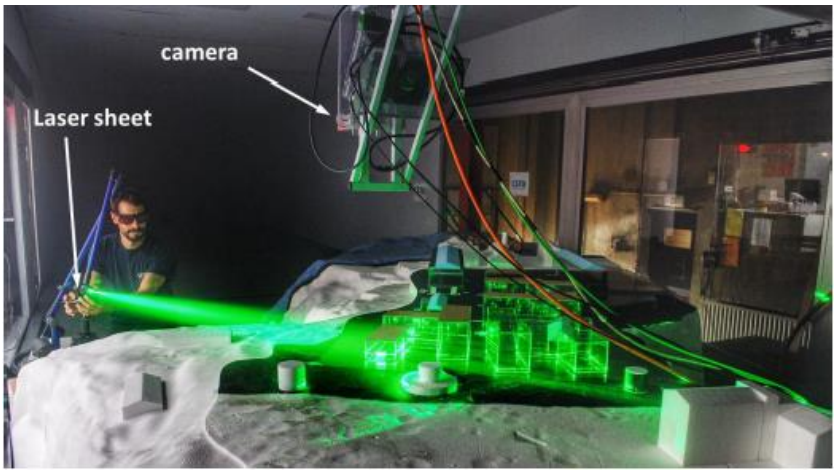


Figure 9 - PIV Measurements

PIV is now quite a common technique for velocity measurements in wind tunnels. Previous attempts were performed to use this technique to assess wind speed close to the ground for pedestrian comfort assessment [2]. There are two main difficulties for one using PIV for pedestrian comfort assessment.
1) Measurements are carried at 1.5 m full scale above the ground, which means 1.5 cm at 1:100th scale. This means that the laser sheet is very close from the ground and will highlight every roughness of the medium used for the ground. This will alter the contrast of the PIV images and will decrease the efficiency of the correlation algorithm which computes the particles movement.
2) The density of the buildings in the district makes the optical access for the laser sheet difficult to set up.
The models were built with Plexiglas faces so that the laser sheet can reach every part of the model where the wind velocity has to be measured. The Plexiglas let the light go through the walls, but will also generate a lot of reflections which will also impair the quality of the PIV images. Special care has to be brought to avoid those reflections adjusting the position of the PIV camera relative to those reflections.
The laser sheet is located 1.5 cm above the ground. To enhance the contrast of the images, the ground was painted with several layers of black paint and fluorescent paint. The later one is obtained by mixing Rhodamine dye with a transparent coating. The green wave length of the laser is absorbed by the dye and is re-emitted in an orange wavelength, which is filtered by the PIV camera filter. This technique dramatically increases the quality of the images, and hence of the measurements.

PIV fields size were 22 cm square. Cross correlations windows were 64pixels large, which yields to a 7 mm resolution. For each PIV field, statistics for average and RMS velocities were calculated from 200 instantaneous pair of images. The convergence of those statistics was checked on the most turbulent areas

Results

Two wind directions were tested 60° and 280°, which are the two directions which were identified on the wind rose. 36 PIV fields were measured for wind directions 280° and 41 PIV fields were performed for wind directions 60°, hence respectively 91600 and 106500 measurements points all over the district model. Figure 10 and Figure 11 present the velocity fields measured at pedestrian level, ie 1.5 cm above the ground model scale. Decimation of the vectors was performed for the readability (1 out of 10 vectors is displayed). It is remembered that without the buildings, the mean wind speed is 6 m/s. The PIV measurements show that on some locations, the velocity exceeds this value which means that the buildings will increase the strength of the wind.

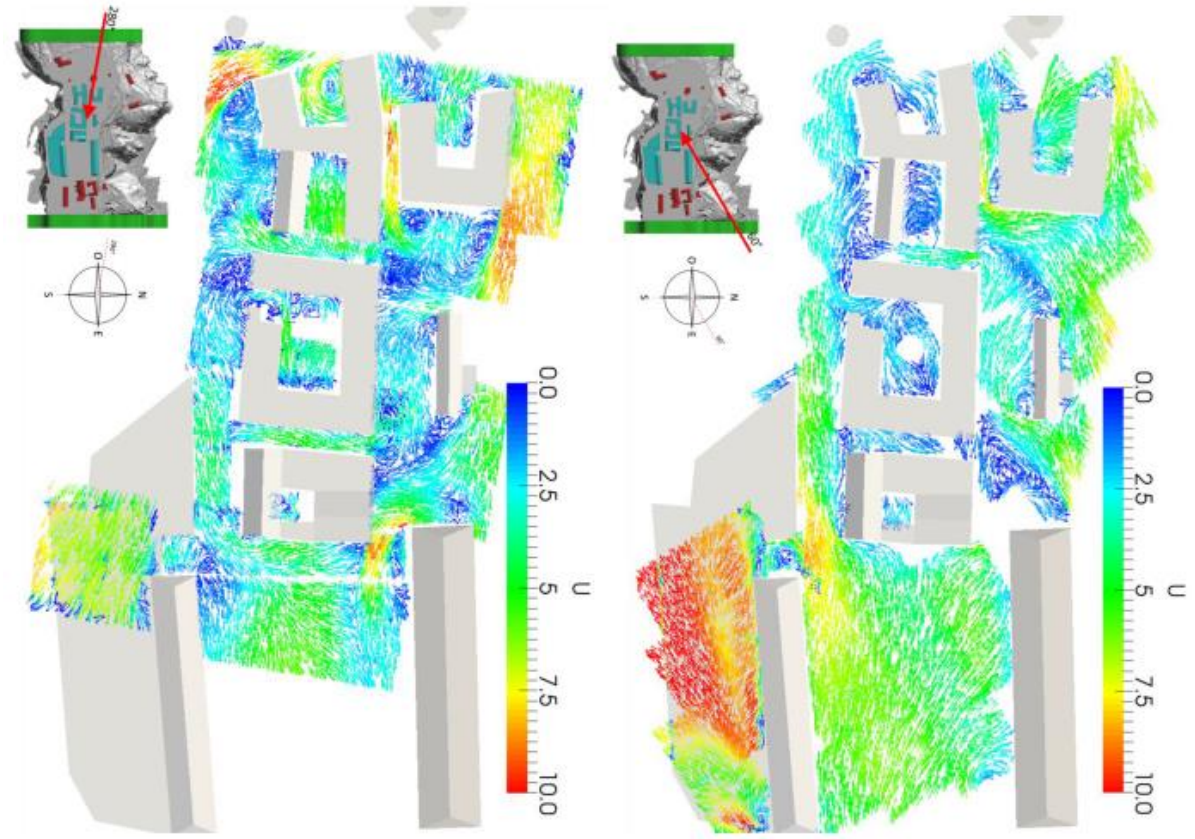


Figure 10 - PIV mean wind speed measurements: left for wind direction 280°; right, for wind directions 60°

In order to quantify the discomfort, the Weibull function calculated on the peninsula are combined with the PIV Measurements. The discomfort criterion here used specifies that discomfort is felt when U + σ > 3.6m/s with U the mean wind speed and the RMS value [1]. Statistics of the wind speed were computed 10 m above the ground without any building. The function $\psi_{i,j}$ is defined for every measurement point j for wind direction i as follows:

$$\psi_{i,j} = \frac{U_{i,j} + \sigma_{i,j}}{\gamma U_{ref}\left(1 + I_{ref}\right)}$$

With $U_{i,j}$ and $\sigma_{i,j}$ the values measured at point j for direction i. U_{ref} and I_{ref} are the mean wind speed and turbulence intensity measured above the peninsula 10m (full scale) above the ground without any building.Υ is the ratio between the velocity measured at pedestrian level and the one measured at 10m (full scale) above the ground. $\psi_{i,j}$ can be seen as a transfer function between the reference point were the weather statistics were computed and any point of the model. The probability $P_{i,j}$ the that $U_{i,j} + \sigma_{i,j} > 3.6$m/s for every measurement point j for wind direction i can thus be written as:

$$P_{i,j} = P_i(U_{i,j} + \sigma_{i,j} > 3.6) = P_i\left(U_{ref} + \sigma_{ref} > {}^{3.6}\!/_{\gamma\psi_j(1+I_{ref\ 10m})}\right) = P_{Di}e^{\left(-\left(\frac{{}^{3.6}\!/_{\gamma\psi_j(1+I_{ref\ 10m})}}{A_i}\right)^{k_i}\right)}$$

Figure 11 present discomfort frequencies calculated from the PIV measurement and the weather statistics from the two wind directions. Results show that for most of the areas, the discomfort frequencies are above 20%. For wind directions 280°, the effect of the buildings increase the discomfort frequencies above 40%. More, one has to keep in mind that the frequencies of both directions should be cumulated. When designing an urban area, CSTB recommends limiting the discomfort frequencies to 2% for the terraces, 10% for strolling areas and less than 20% for fast pace walking. The discomfort frequencies which have been calculated for this first version are dramatically high and need to be reduced.

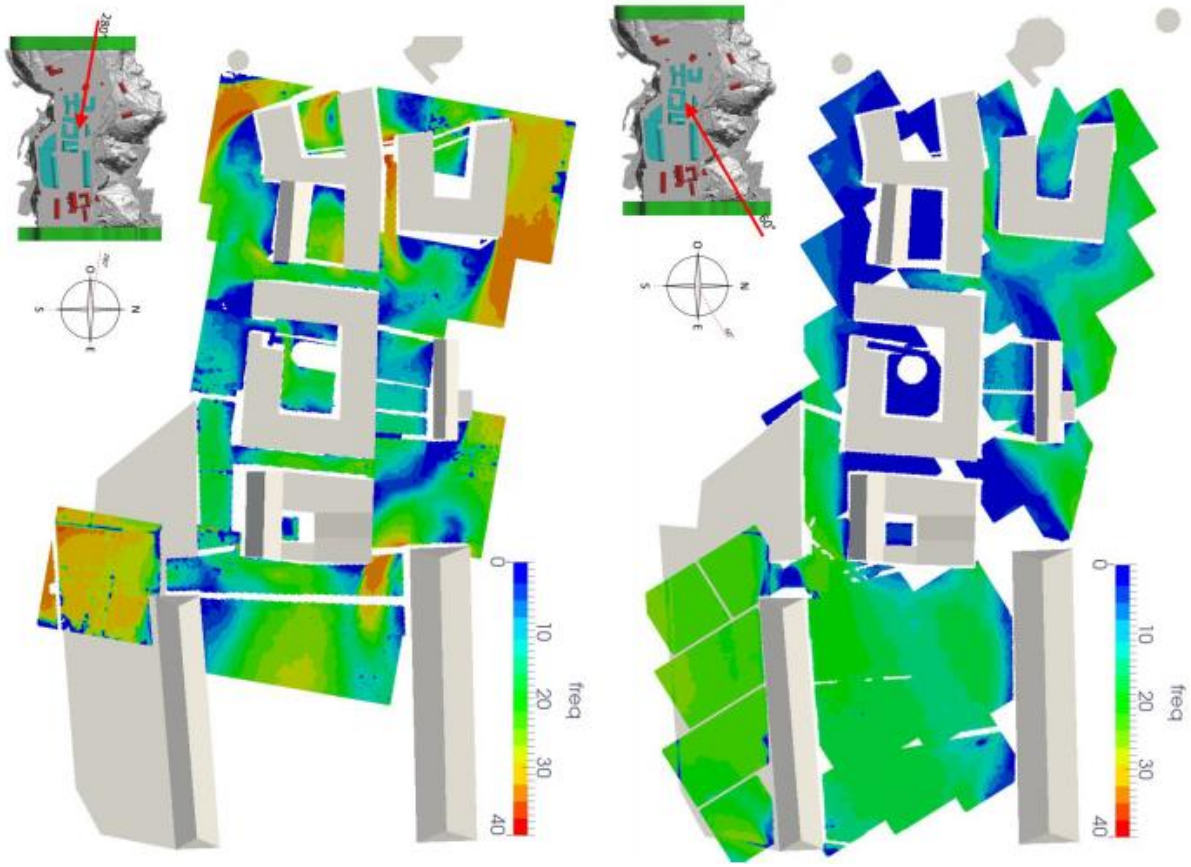


Figure 11 - Discomfort frequencies calculated from PIV measurements: left for wind direction 280°; right, for wind direction 60°

GEOMETRY OPTIMIZATION USING CFD

Urbalterre's urban architects hence used CFD in order to optimize the design regarding pedestrian wind comfort. They ran the simulations by themselves using the Meteodyn's dedicated CFD software UrbaWind

CFD Computation with Urbawind

The CFD method of UrbaWind consists in solving the Reynolds-Averaged Navier-Stokes equations on an unstructured rectangular grid with automatic refinement of the mesh near obstacles. The CFD tool delivers the tri-dimensional mean velocity field, the turbulence energy field and the mean pressure for each point in the domain. Closure of the RANS equation is achieved using a transport equation on the kinetic energy and an estimation of the eddy length scale based on the wall distance. The equations resolution is based on a finite volume method with a rectangular multi-bloc refined mesh. A very efficient coupled multi-grid solver is used for a fast convergence for every kind of geometry [4].
The UrbaWind software allows the boundary conditions to be generated automatically. The mean velocity profile at the computational domain inlet is determined by the logarithmic law in the surface layer, and by the Ekman function above [5]. A 'Blasius'-type ground law is implemented to model frictions (velocity components and turbulent kinetic energy) at the surfaces (ground and buildings). The effect of porous obstacles is modeled by introducing a volume drag force in the cells lying inside the obstacle.
The building definition and topography of Montlaur Citadel were modeled with at least 0.5 m accuracy in order to ensure a correct calculation of speed up and turbulence intensity.
The computational domain is a cube of 1 km side with a mesh accuracy of 0.5 m around obstacles and expanding above the urban layer canopy and contains 3.3 million of cells. Mesh and computational domain are presented Figure 12.
The wind profile prescribed at the inlet will depends of the roughness outside of the computational box for a given wind direction. Two main sectors of roughness lengths can be derived from the analysis of the surrounding roughness: water from 135°(South East) to 280° (West by North) and 0.3 m for the other wind directions.
Computational time for a given wind direction vary from 150 min to 400 min on an Intel Xeon E5-2609 at 2.4 GHz.

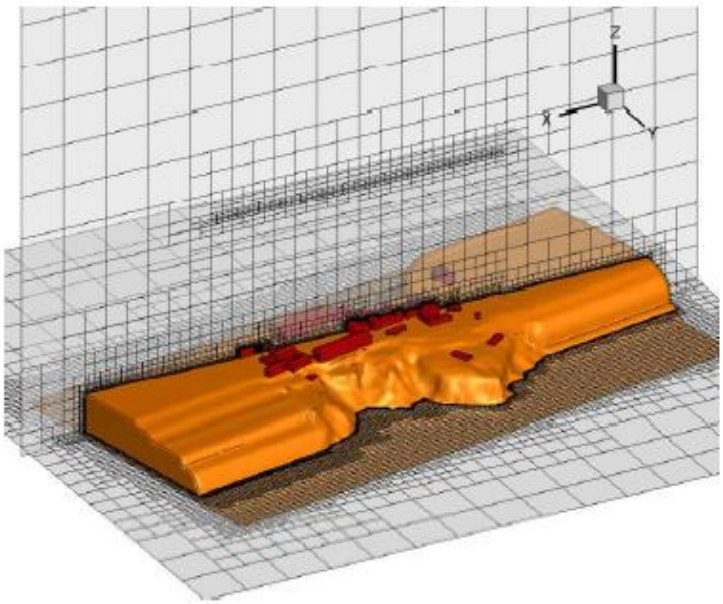


Figure 12 - Computational domain

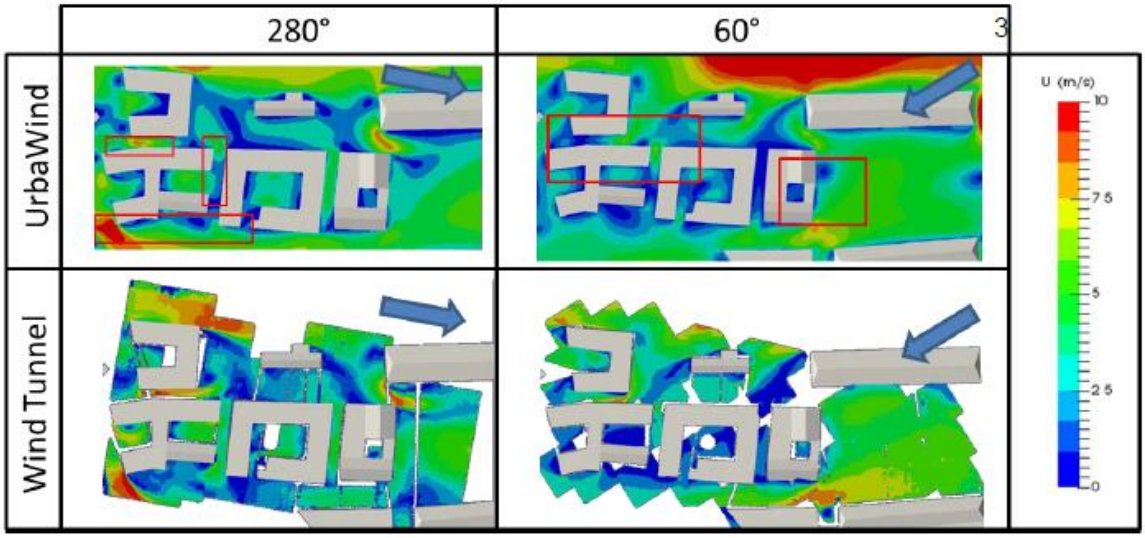


Figure 13 – Comparison of mean wind speed at pedestrian level

On Figure 13, mean speed value from CFD simulation of Urbawind is compared to the PIV measurements carried out the first version of the district. The computed mean speed shows good correlation with measurements. The most important flow features, including recirculation behind buildings, Venturi effect between the buildings or corner accelerations are well reproduced. One may notice that on some parts of the district highlighted by red squares, Venturi effects have lower values with CFD compared to experimental data.

The wind comfort criterion can also be calculated from the CFD results in a similar way as it was computed from the wind tunnel results. Figure 14 presents a comparison between discomfort frequencies obtained with the CFD and with the wind tunnel approach. One can see that the order of magnitude is the same. Discomfort frequencies computed from CFD tends to be lower for some Venturi effects than from wind tunnel results.

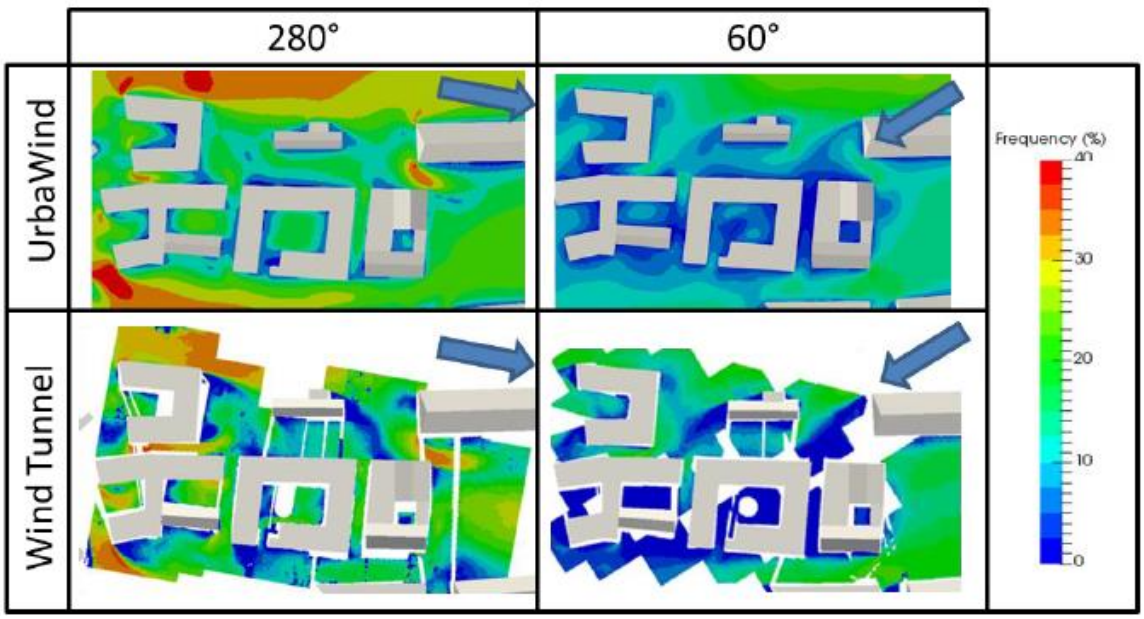


Figure 14 - Comparison of Discomfort frequencies

Optimization of the district design

The simulations which were run on the first version of the district showed that the results obtained with UrbaWind yields to the same conclusions regarding pedestrian wind comfort. This tool has hence been used by the urban architect to iterate some solution to enhance the pedestrian wind comfort. Urbalterre's urban architects ran successively 6 designs of the district. For each one, a different windbreak solution has been tested. Table 1 sums up the 6 configurations investigated:

Case n°	Windbreaks	Example
0	Reference case	
1	Canopy	
2	Porous elements (20% porosity)	
3	Building	
4	Elongated porous elements (10 m high; 50% porosity)	
5	Trees in row (30 % porosity)	
6	Porous elements at 4 meters above the ground (4m high, 20 % porosity)	

Table 1 – Windbreaks strategy

From the reference case (Figure 15), strategies to reduce wind speed show that:

- The canopy windbreak (case 1 on Figure 16) is efficient for both dominant winds mostly on the North side. Wind is in fact deflected upward by upstream buildings. The canopy prevents wind from diving into the place.
- Porous elements located in staggered rows (case 2 on Figure 17) are also very efficient locally for 280° wind direction mostly on the North side. Nevertheless, this windbreak is not very efficient for 60° wind direction.
- Building on the West part (case 3 on Figure 18) is only efficient for 280° direction on a limited area of 25% of the total place thanks to the blockage effect
- Elongated porous elements (case 4 on Figure 19) is efficient on a very limited area for 280° wind direction only. There is no improvement for wind comfort for 60° wind direction.
- Trees in a row (case 5 on Figure 20) are the best strategy here. For 280° wind direction, over 75% of the place mean speed has been divided by 50 % at least. For 60° wind direction, the efficiency is less compared to 280° but the wind speed decreases by at least 25%.
- Porous elements located at 4 m above the ground (case 6 on Figure 20) do not provide sufficient protection for the place

Except for case n°6, all strategies have positive effect on the mean speed. The case n°5 is the most efficient.

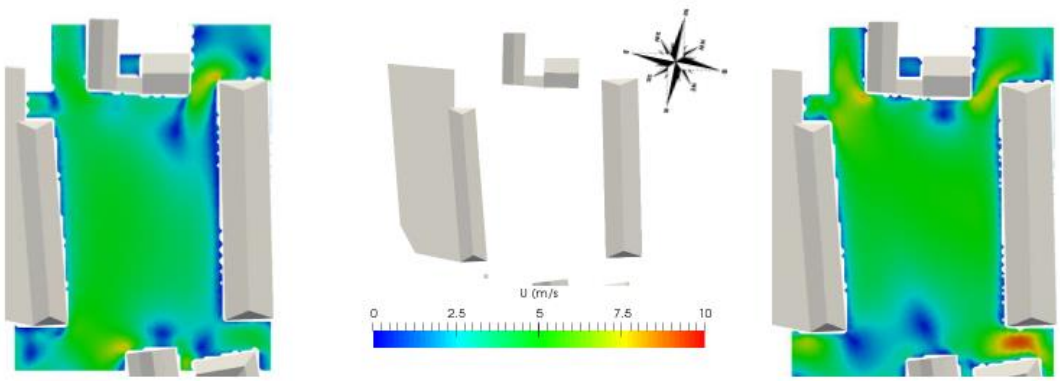


Figure 15 – Mean speed for case 0: left for wind direction 280°; right, for wind directions 60°

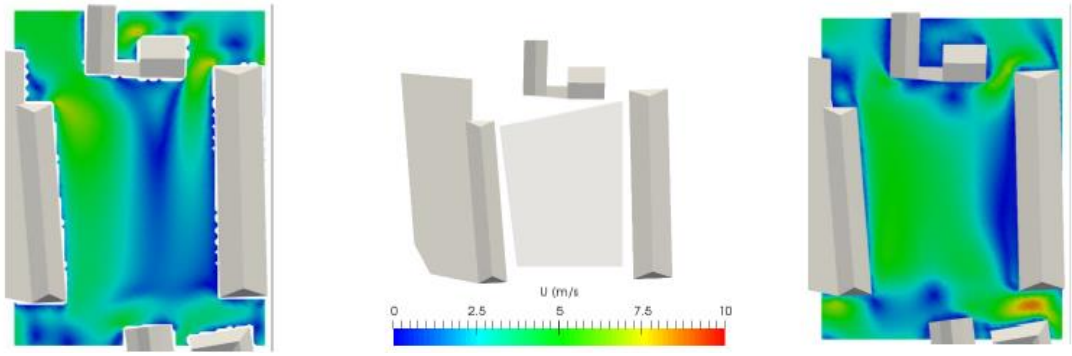


Figure 16 - Mean speed for case 1: left for wind direction 280°; right, for wind directions 60°

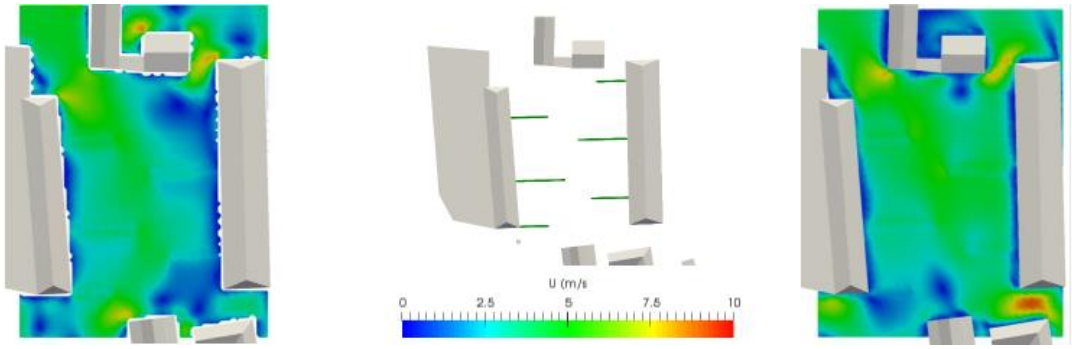


Figure 17 - Mean speed for case 2: left for wind direction 280°; right, for wind directions 60°

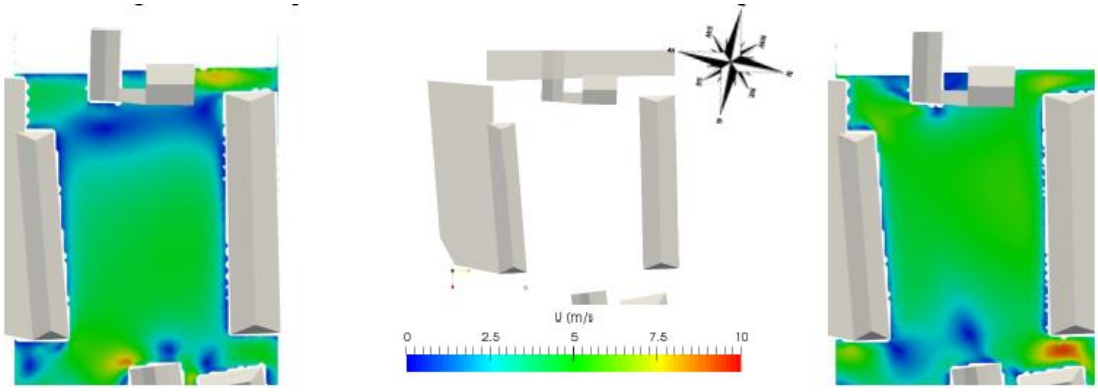


Figure 18 - Mean speed for case 3: left for wind direction 280°; right, for wind directions 60°

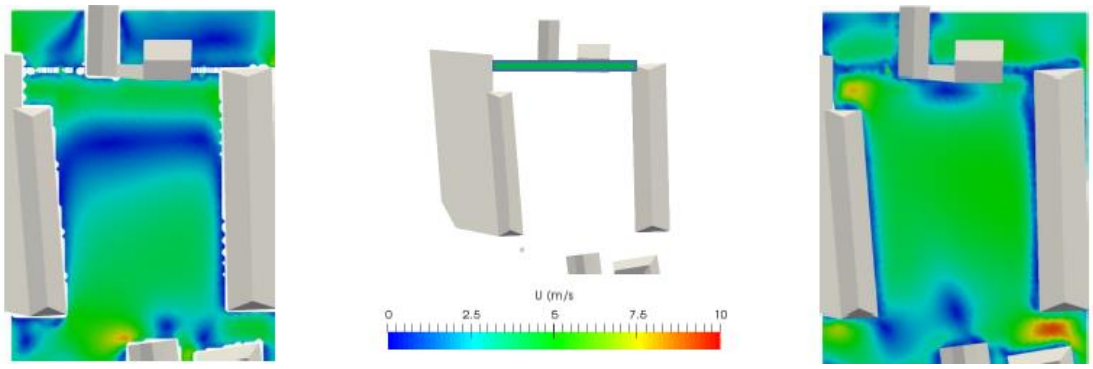


Figure 19 - Mean speed for case 4: left for wind direction 280°; right, for wind directions 60°

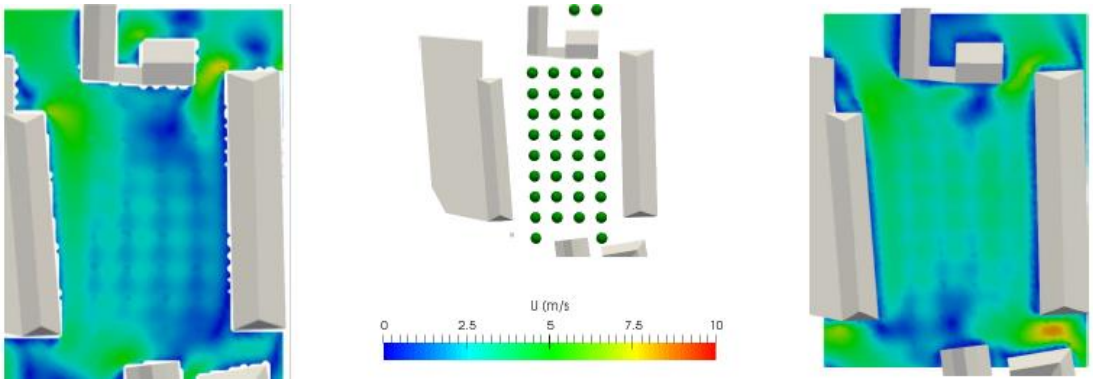


Figure 20 -Mean speed for case 5: left for wind direction 280°; right, for wind directions 60°

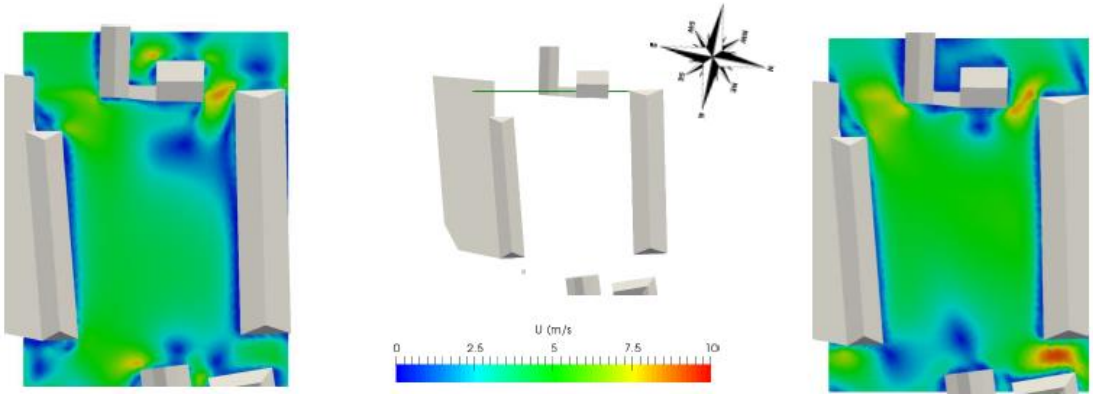


Figure 21 - Mean speed for case 6: left for wind direction 280°; right, for wind directions 60°

Vegetation is indeed a very effective tool to enhance pedestrian comfort. Urbalterre ultimately designed a version of the district based on the use of the vegetation as presented in Figure 22. Urbalterre chose to limit the number of new buildings, presented in red, and to use a lot of vegetation. Bright green areas represent trees, dark green areas low dense vegetation typical of the Mediterranean area (garrigues). Orange lines represent some barriers stuck close to the vegetation.

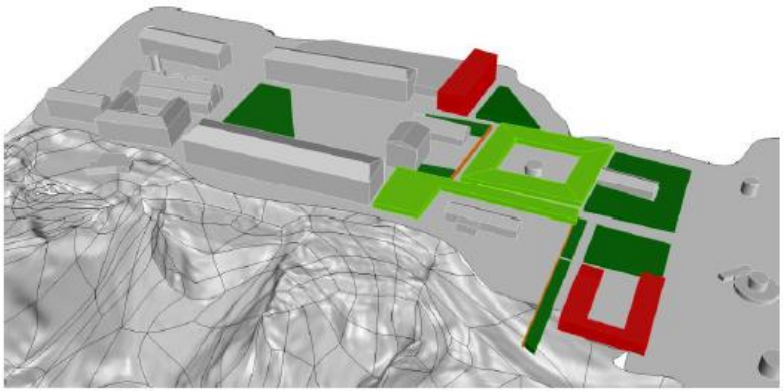


Figure 22 – Final version of the district

Figure 23 presented the discomfort frequencies calculated with CFD on the final design of the Montlaur Citadel. Results show that the discomfort frequencies have been largely been reduced. The vegetation introduces a porosity which slows the wind velocities on some walking area.

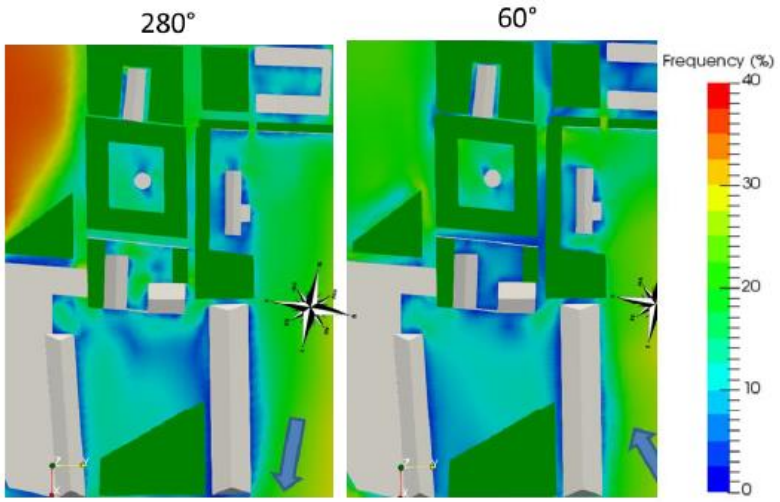


Figure 23 – Discomfort frequencies calculated with Urbawind for the final iteration

ASSESSMENT OF PEDESTRIAN CONFIGURATION IN THE FINAL CONFIGURATION

In order to check the efficiency of this last iteration, a new test in wind tunnel has been setup. Figure 24 presents wind tunnel model used for the final version. Vegetation was modeled using real lichens which were implemented according to the density of the vegetation planned by Urbalterre. The main problem with Lichens is that there are not transparent. This make the optical access of the laser sheet even more difficult to set up.

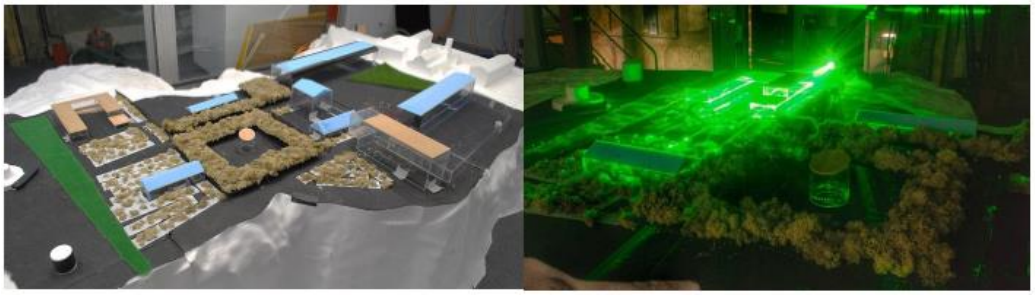


Figure 24 - Wind Tunnel model of the final version of the district

Measurements were run for the two wind directions. 27 PIV fields were performed for wind directions 280° and 33 PIV fields for wind direction 60°. They were intended to cover the areas expected to be used by the pedestrians.
Figure 25 presents the discomfort frequencies computed from the PIV measurements carried out in the Wind Tunnel.

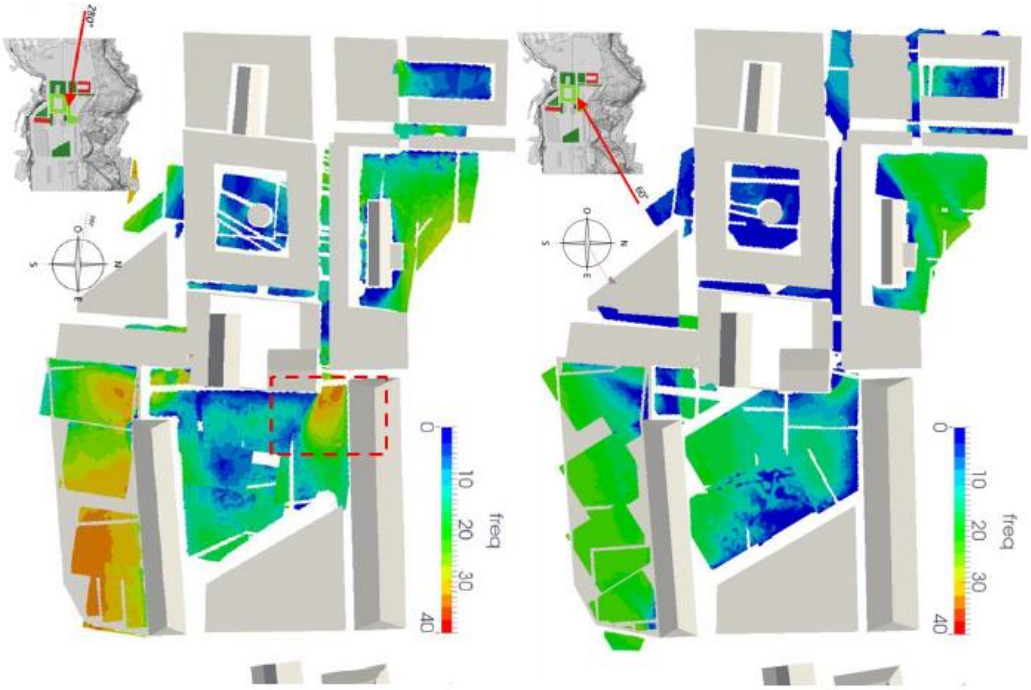


Figure 25 - Discomfort frequencies calculated from PIV measurements: left for wind direction 280°; right, for wind directions 60°

Discomfort frequencies which were measured were similar to the ones obtained through CFD. One can observe that the comfort has actually been enhanced compared to the first iteration. Discomfort frequencies remain high, and this is mainly due to strong wind blowing over the peninsula. The main issue for Urbalterre was the corner of the large square between the two ancient barracks highlighted in Figure 25 with as dashed square. Here a Venturi effect can clearly be seen between the two buildings and may cause a severe discomfort for the pedestrians. This effect has been underestimated by the CFD approach. It was the proposed to optimize this issue in the wind tunnel iterating with vegetation and assessing its effect with PIV measurements
Figure 26 presents two steps of the iteration process using several lichens. The first step was to create a vegetal porch hanging between the two buildings. The velocity at the pedestrian level was reduced, but it was not considered as sufficient. Then, two additional vegetation patches were set down on both

side of the porch in a chicane configuration. Results show that the wind speed is dramatically decreased in this configuration. Again vegetation remains a very interesting leverage for correcting such flow features.

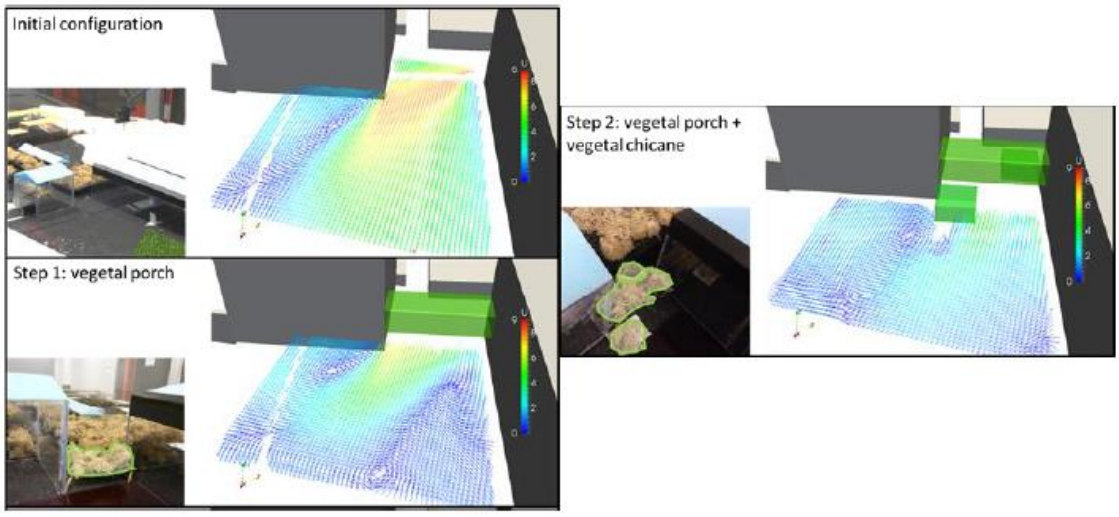


Figure 26 - Optimization of the Venturi effect using vegetation and PIV measurements

CONCLUSION

This paper presented a study on the optimization of the pedestrian comfort in the citadel of Bonifacio, the windiest city of Europe. Urbalterre, the urban architect agency in charge of the project combined Wind Tunnel and CFD simulations to assess and optimize the pedestrian wind confront.

The first step was an evaluation of the wind statistics at the district location. Weather data from the nearest weather station was extrapolated to Bonifacio using CFD simulations on a domain of several kilometers to take into account the local orography and roughness. The design of the district was then performed in three steps.

A first assessment was carried out in wind tunnel using Particle Image Velocimetry. To our knowledge, very few studies used this type of measurements to assess wind comfort. This kind of measurements indeed requires special care to obtain sufficient accuracy due to the proximity of the laser sheet from the ground. Velocity measurements were combined with weather data to compute a wind comfort criterion. Results highlighted severe comfort issues which require an optimization of the district.

A second step consists of optimization carried out by the urban architects of Urbalterre themselves thanks to the UrbaWind CFD solution. Good correlations between wind tunnel and CFD results were observed. On some locations, CFD results presented lower wind mean speed values for some Venturi effects compared to the wind tunnel results. CFD tool allowed the urban architects to iterate several versions of the district and to convergence towards an optimal solution.

The use of vegetation leads to an optimized version of the district which was finally tested again in the wind tunnel. Final adjustments were performed directly in the wind tunnel using PIV measurements to optimize a Venturi effect between two buildings.

The main interest of this study is the combination of PIV measurements, which proved to be a very efficient tool to assess wind comfort in wind tunnel, and CFD simulations which were carried out by the urban architects themselves to iterate various solutions.

The configuration of the Montlaur Citadel, due its location above 60m cliffs and the impressive statistics of the wind blowing on the South of Corsica Island, was a tough challenge regarding the optimization of pedestrian wind comfort. Again, the use of the vegetation has proven to be one of the most efficient way to optimize pedestrian wind comfort when designing a urban area.

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