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Analysis of Aerodynamic Performances of an Individual House Using CFD Numerical Methods

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Abstract – **The article observes the effects of winds that emerge in the context of climatic changes on an individual house depending on its architectural form. The analysis is based on a CFD (computational fluid dynamics) method of approach. The results could provide a way to prevent human and financial loss caused by storms. The numerical calculations ware done using software called ANSYS that is in the possession of The Faculty of Naval Architecture "Dunarea de Jos" University. Different angle wind tests indicate that both the integrity of architectural elements and comfort inside and around a building can be affected. Future architectural forms should consider air circulation and patterns from the concept phase of design in order to prevent deterioration to specific buildings or components of a building.**

Keywords – CFD, flow pattern, turbulence, velocity, vortices

1. INTRODUCTION

Over time, for the study of wind flow around different types of buildings and constructions, scientists have used experimental methods. Even though they produce positive practical results, they are quite expensive due to the fact that they imply building physical models and require access to wind tunnel in which these models have to be placed in order to be tested in optimal conditions. The resulting conclusions are more about quality than quantity. Therefore, in order to optimize a specific model shape multiple tests are required, further expanding the budget needed to reach a satisfying outcome. Technological progress has made it possible for analytical and numerical methods to emerge, that could help predict the way air flows around objects. These methods are now known as CFD which stands for Computational Fluid Dynamics.

Aerodynamics as part of fluid dynamics, describes the laws of air and other gases flows. Consequentially it also describes other emerging forces that occur on solid surfaces during this process. The study of aerodynamics has been used in the production of multiple complex objects such as aeroplanes, cars, wind turbines, which require good knowledge regarding their response to high-speed winds. In architecture and civil engineering, aerodynamics has started picking up importance with the necessity of building higher and in the context of climatic changes. Both complex structures like wide span bridges, skyscrapers, and small individual houses, should consider CFD studies in order to prevent their deterioration or even total collapse against winds.

Using a computational method such as CFD, air flow can be studied thoroughly both in the conception phase of the design and through time if conditions change. Weak spots where turbulent flows occur can be easily detected and measures can be taken accordingly. Numerical efforts differ depending on the shape that is tested and range from more complex to simpler ones. At high speeds when turbulent flows emerge, the numerical effort can be reduced by applying turbulence models. In order to minimize the numerical effort it is optimal to reach a satisfying compromise between the effort and the level of turbulence model. Well known reference turbulence models are $k - \varepsilon$ or $k - \omega$.

In this article, we are observing wind flow around an individual house in different situations and at different incidence angles [1], [2], [3]. The results will be used to minimize the effects of wind on the house, its components and on the comfort of the inhabitants in the residential unit and around it (more specifically in the exterior dining area).

For the numerical calculations we use the ANSYS software, whose license is in possession of the University “Dunarea de Jos” in the city of Galați [4], [5].

Wind speeds are the ones found locally in the specific area of the city of Galati where the house will be built, and are provided by “The design code for evaluation of wind effects on buildings” designation number CR 1-1-4/2012. The value for the dynamic pressure of the wind is 0.6 kPa [6], [7] (Fig. 1).

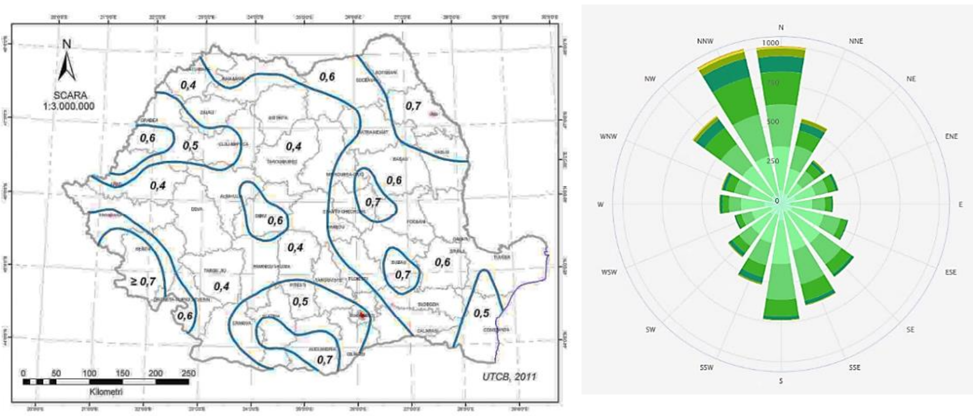


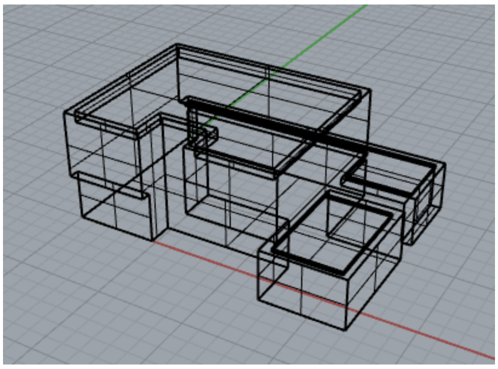
Fig. 1 Wind flow and pressure for the South-Est geographical area of Romania

The numerical models used for observing how air flows around the house are the following:

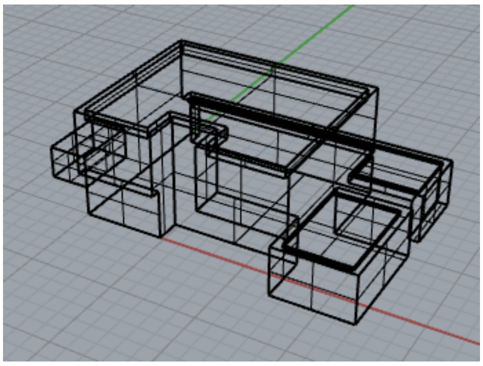
a) Without vegetation;
b) Without vegetation + the outdoor dining table;
c) With high vegetation + low vegetation;
d) High vegetation + low vegetation + outdoor dining table;
e) High vegetation + outdoor dining table,

where the simulated vegetation that is placed on the model consists of 2 trees with a height of 7 – 10m, positioned on the North-West side of the plot, and a green fence of 5 to 7 shrubs with a height of 2.5 – 3.5m, positioned on the left side of the house. The plot presents itself as relative flat and without no consequence on the wind study.

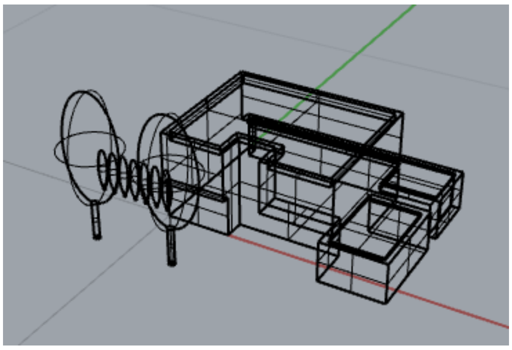
Models a), b), c), d), and e) are presented in figure 2. In order for the digital models to be imported in the CFD analysis software, they were built inside Rhinoceros and exported as igs format that is accepted by ANSYS. This format was preferred as the following stages of the experiments can be processed faster by the analysis software.



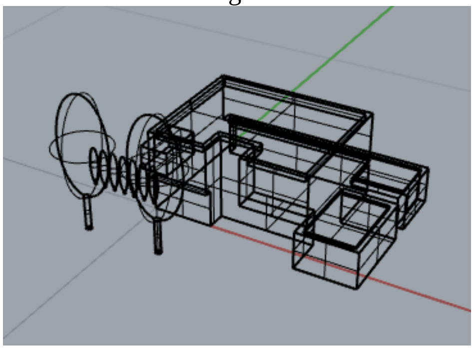
a) model without vegetation



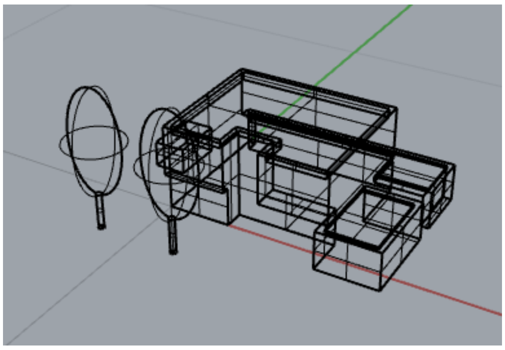
b) model without vegetation + outdoor dining table



c) model with high and low vegetation



d) model with high and low vegetation + outdoor dining table



e) model with high vegetation + outdoor dining table

Fig. 2 Digital models that are tested

2. METHOD OF THE EXPERIMENT

CFD methods try to simulate the interaction of liquids and gases that come in contact with surfaces governed by limited conditions. They also study the flow of solids passing through a system. These models are based on the principles that emerge from Navier-Stokes equations [4], which in their most general form are as following:

$$\frac{d\vec{V}}{dt} = \vec{f} - \frac{1}{\rho} grad\left(p\right) + \nu \Delta \vec{V} \quad (1)$$

where:

- $\vec{V}$ - represent the translation speed vector;
- $\vec{f}$ - represent the mass forces;
- ρ - represents the fluid density;
- p - represents the pressure tensor;

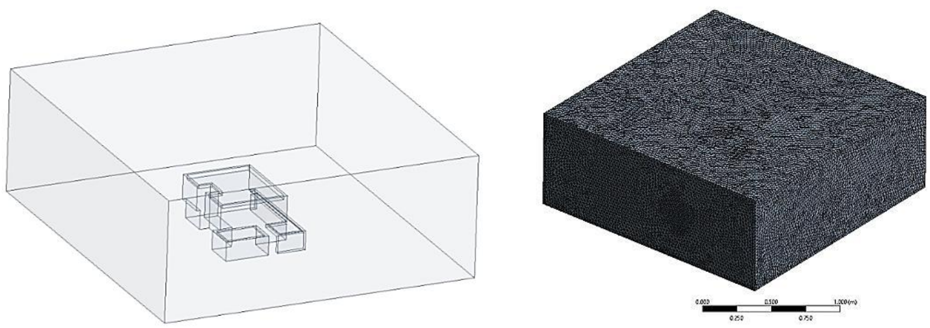
A CFD experiment consists of the following stages:

1. Meshing of the test structure in finite volumes

The finite volume is a component that is part of the structure to be analysed. These components are interconnected through nodes and lines. An ideal structure with a correctly chosen number of finite volumes can provide results that are within an acceptable margin of error. For a higher precision the size of the volumes should be minimal, in which case the processing power for the needed calculations is the largest. Smaller meshes need less processing power but provide imprecise results.

ANSYS CFS has the ability to mesh a specific volume to the required level of detail, while preserving mass, impulse and energy.

For our specific model of an individual house the software encompasses the volume as presented in figure 3 a). The meshed volume that is divided in 700.000 finite elements can be seen in figure 3 b).



a) b)

Fig. 3 Meshed volume

We notice that the house along with the vegetation and the outdoor dining table act as negatives within the meshed volume. Basically, the house is a cut-out in the box shaped volume.

2. Conditions and try-outs

In general conditions of the experiment refer to pressure, speed, intensity of the turbulences and temperature. Figure 4 shows the nodes where the specific conditions were applied. The conditions are similar to the ones found at the geographical location of the individual house.

The applied forces consist of the wind speed given by [5] 5.25 m/s, taking into consideration the requirements of [6] presented in figure 1.

Taking into consideration the main direction of wind mentioned in [6] the numerical analysis was done for incidence angles ranging from -20°, -10°, 0°, 10°, 20° as presented in figure 5.

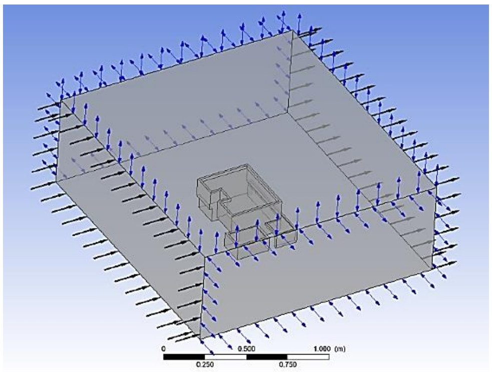


Fig. 4 Applied forces

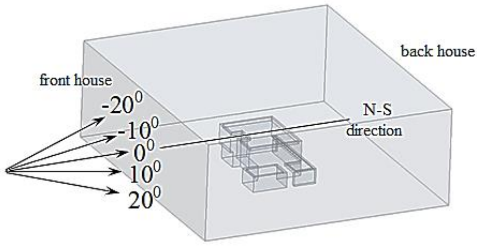


Fig. 5 Angles of incidence

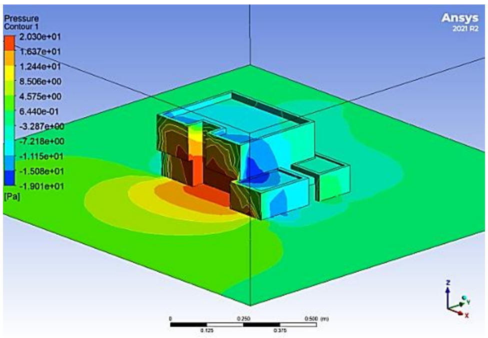
The values of the angles of incidence were chosen as to minimize the processing time and to abide by the national design regulations [6].

3. RESULTS

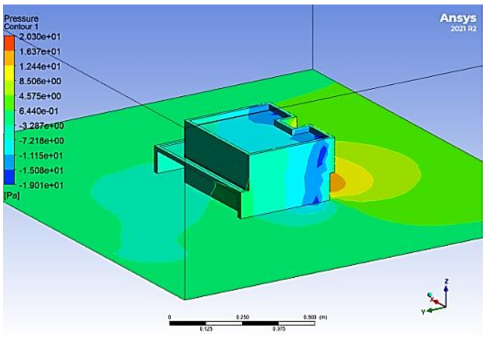
The processing of the calculations done for each incidence angle took about 6 hours. The resulting graphical representations are shown in figure 6.

The analysis of the results is done both for the pressures and the speeds that occur around the digital model. The pressure analysis aims to highlight possible damaging forces that act on different architectural elements of the building. The wind speed analysis will determine the areas where air stagnates or otherwise increase in velocity. In case of air stagnation debris, dust or snow can settle and pile up in an unwanted manner. In contrast an increase of wind speed can pull away construction elements such as windows, gutters, and even parts of the roof.

For the study presented in the paper, it is also interesting to remember the influences that the action of the air flow around ground constructions, domestic or industrial, can have on their foundations. Thus, depending on the pressures on the surfaces exposed to air currents, important reactions may occur at the foundation level that must be known from the design phase. These reactions (forces and moments) can negatively influence the stability of the constructions. Also, negative influences can appear if the foundations are oversized, leading to an unjustified increase in costs.

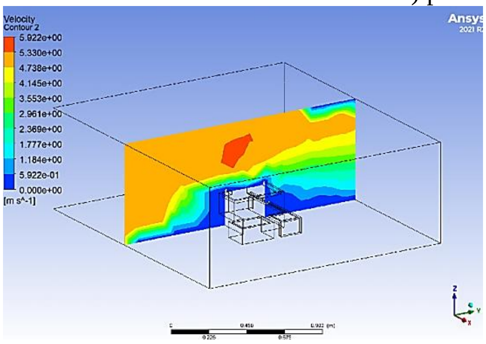


a1) north elevation

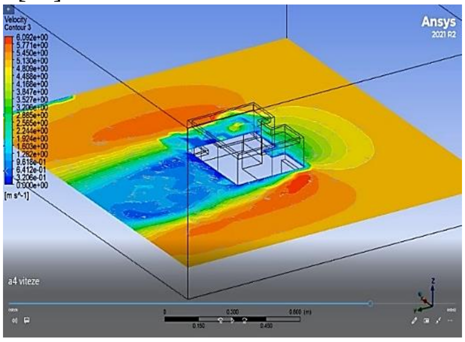


a2) south elevation

a) pressure [Pa]



b) speeds in mid vertical plane



c) speeds in mid horizontal plane

a) speed [m/s]

Fig. 6 Distribution of wind speeds and pressures

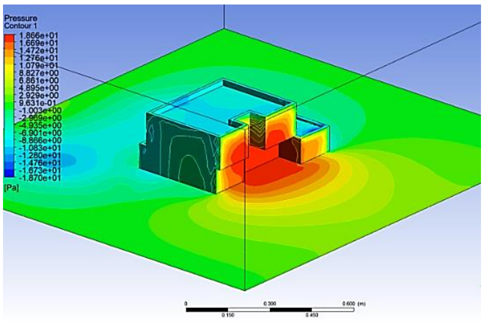
4. CONCLUSIONS

4.1 Specific conclusions

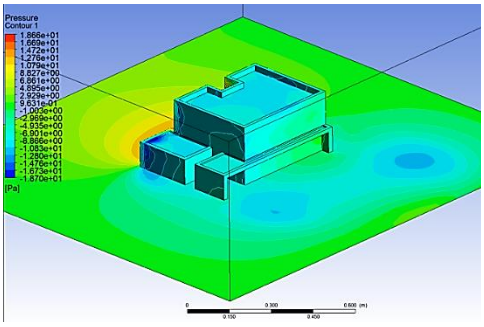
4.1.1 Model without vegetation

The pressure analysis done on the digital model at an incidence angle of 0° for the wind direction is presented in figure 7 a). The wind speed variations for the same angle of incidence can be observed in figure 7 b).

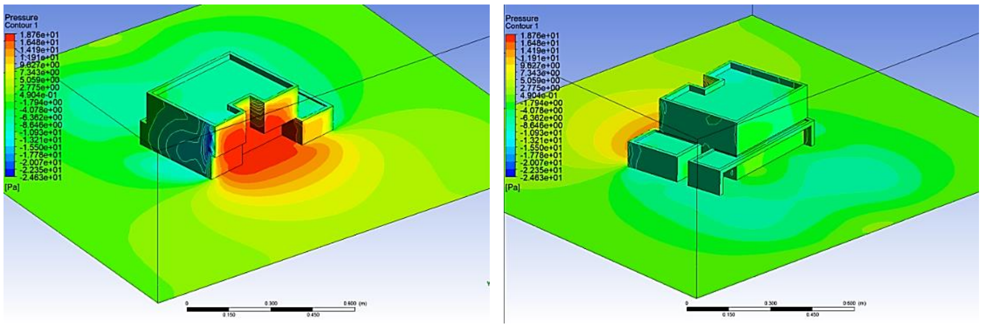
North elevation



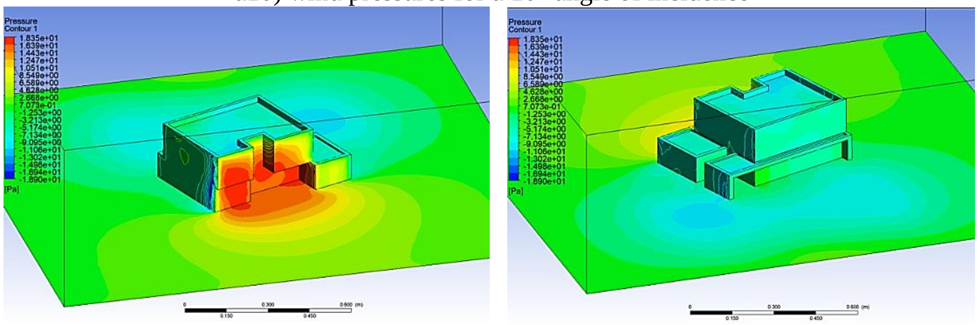
South elevation



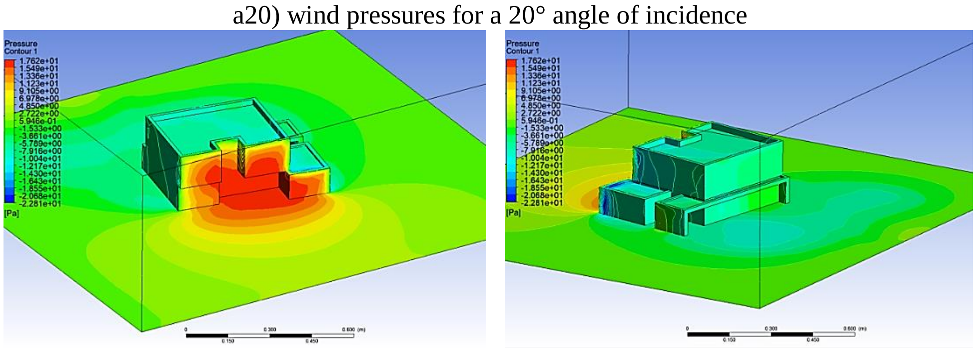
a0) wind pressures for 0° angle of incidence



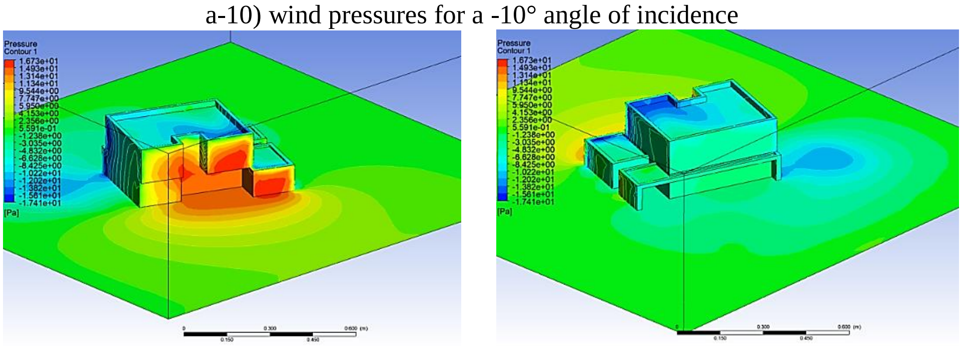
a10) wind pressures for a 10° angle of incidence



a20) wind pressures for a 20° angle of incidence

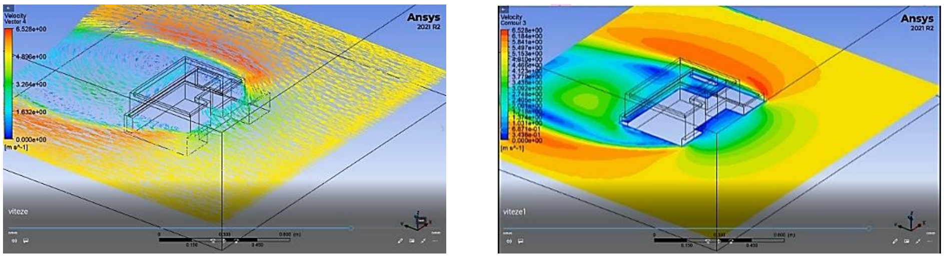


a-10) wind pressures for a -10° angle of incidence

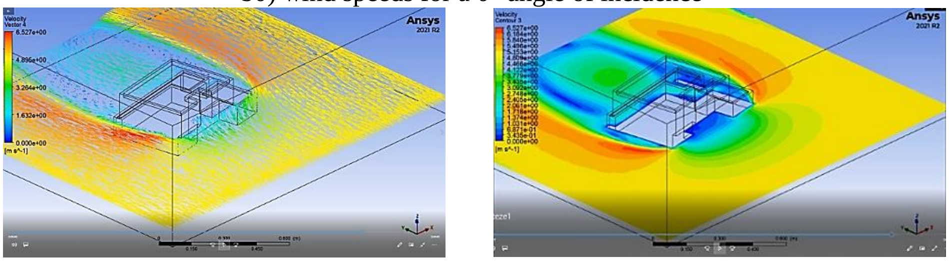


a-20) wind pressures for -20° angle of incidence

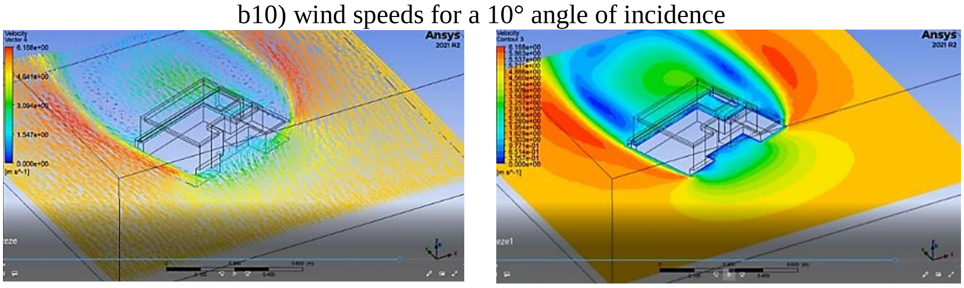
a) pressure variations on the surfaces of the model



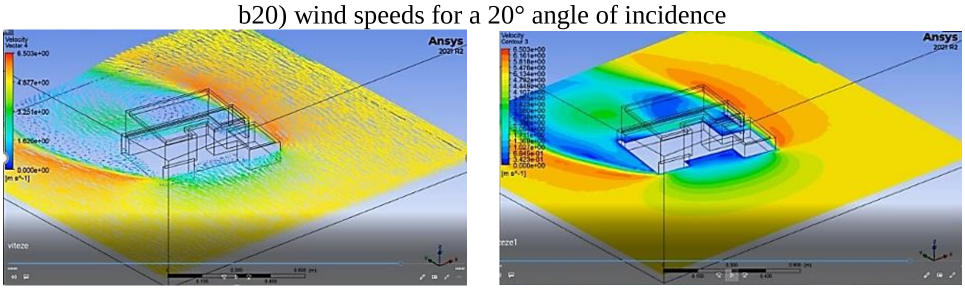
b0) wind speeds for a 0° angle of incidence



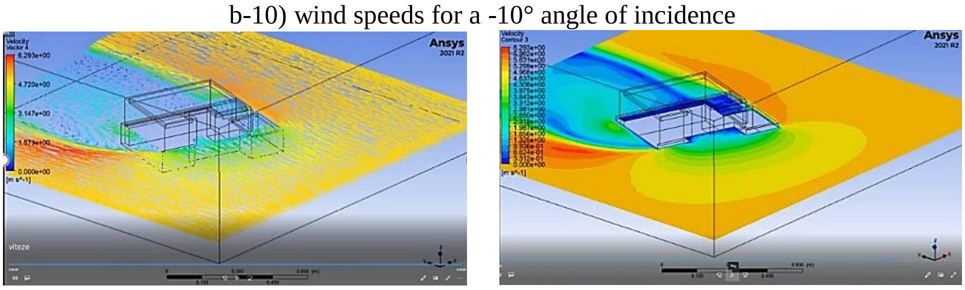
b10) wind speeds for a 10° angle of incidence



b20) wind speeds for a 20° angle of incidence



b-10) wind speeds for a -10° angle of incidence



b-20) wind speeds for a -20° angle of incidence

b) wind speeds variations around the model

Fig. 7 Model without vegetation

From the analysis of the pressure distribution across the surfaces of the model we can draw some conclusions.

In figures a0) to a-20) we can observe that on surfaces that come first into contact with the wind, pressures occur that vary according to the angle of incidence for a constant wind speed of 5.25m/s. Regarding the air speed around the model we notice the speed increases at the building corners meaning that it can pull the window sills of the roof gutters. When coming in contact with large impermeable surfaces the speed decreases. The values are recorded in Table 1.

Table 1 Pressure variation on the model surfaces according to the angle of incidence

Incidence angle	**Maximal pressures**	**Minimal pressures**
[^{o}]	[Pa]	
20	18.35	-18.90
10	18.76	-24.63
0	18.66	-18.70
-10	17.62	-22.81
-20	16.73	-17.41

A graphical representation of the pressure variation can be observed in figure 8.

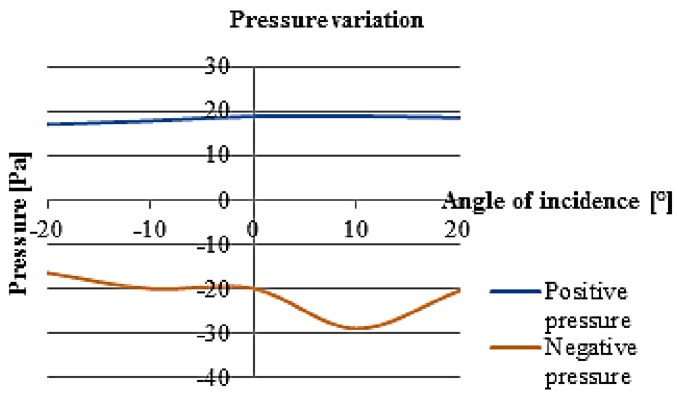


Fig. 8 Pressure variation

By analysing the pressure variation both in figure 7 and in the graphical representation of maximal and minimal pressures in figure 8 we can conclude that:

a) The most unfavourable case for the direction of the wind is from an angle of incidence of 10° to the North-South orientation of the individual house which coincides, as seen in figure 1, with the main direction of the wind found locally (NNW-SSE). It is followed by the 0° incidence angle that coincides with the N-S direction of the wind. In both cases it can lead to both discomfort to the inhabitants and deterioration to the individual house and its architectural elements.

b) The most favourable situation is for a -20° angle of incidence for the wind direction. This is rarely the case for the city of Galati as we notice from figure 1.

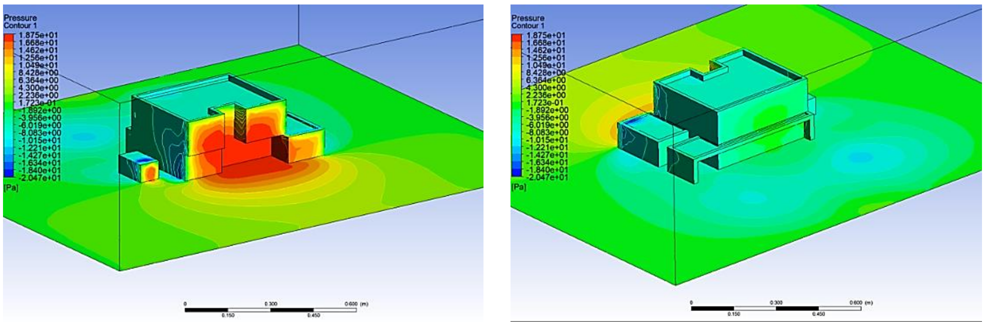
c) In figures 7 a0) and a-20) we notice that on the south elevation (a0)) and on the west elevation (a-20)) some depression occurs. This can be beneficial as the area is protected from the wind and residents can enjoy outdoor activities such as reading a newspaper or playing. It also means that the area would need more cleaning as dust or snow can settle and pile up.

d) The presence of the attic on the upper part of the attic we notice a depression phenomenon that leads to a settling of debris such as dust or leaves. On the other hand, on the exterior of the attic we can see an increase of speed that can pull elements such as gutters. Therefor the fixture accessories must be chosen with care. The increase in speed around the model is by 1.2 m/s at maximum.

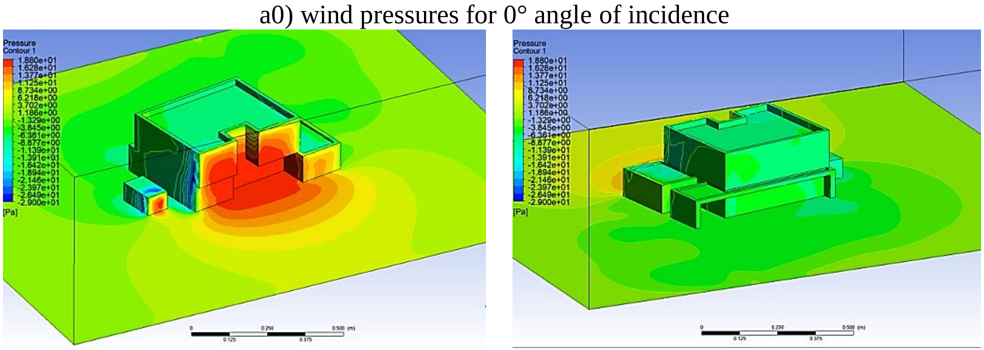
4.1.2 Model without vegetation + outdoor dining table

The experiments done previously are redone with an additional placement of the outdoor dining area that the beneficiary of the project intends to arrange on the East elevation. Therefore, the projection of pressure variation of the model with the dining area accessories are presented in figure 9 a). The air circulation speeds around the model are shown in the projections in figure 9 b).

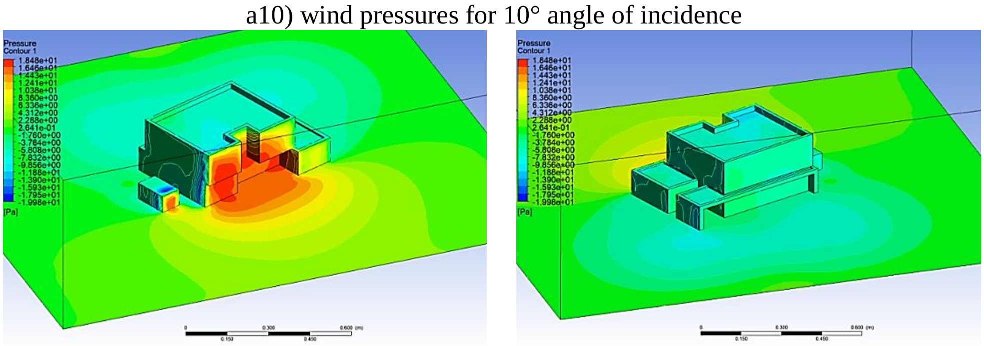
North elevation South elevation



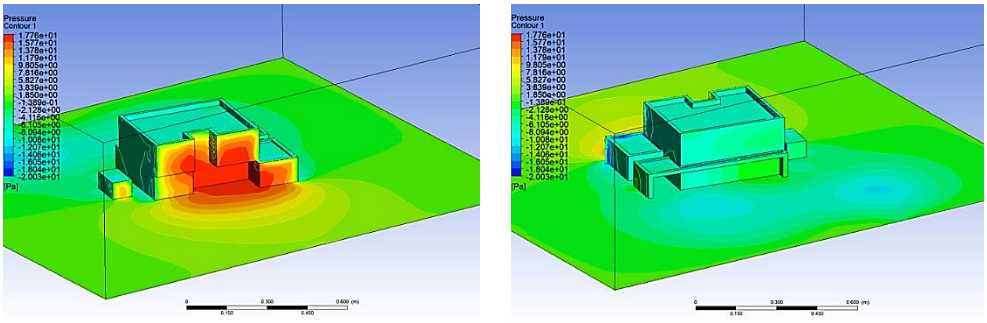
a0) wind pressures for 0° angle of incidence



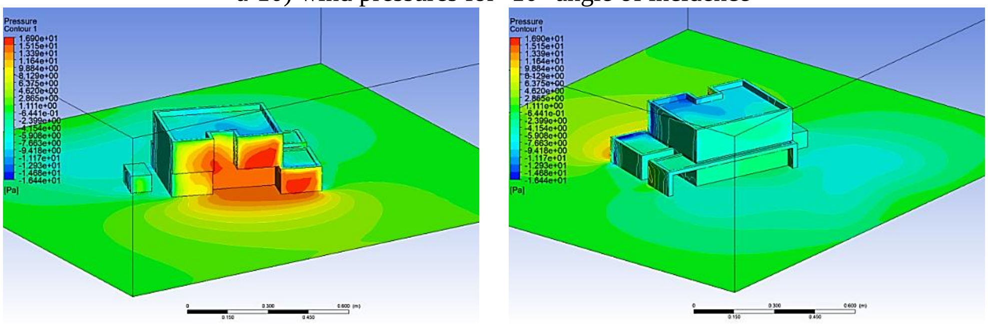
a10) wind pressures for 10° angle of incidence



a20) wind pressures for 20° angle of incidence

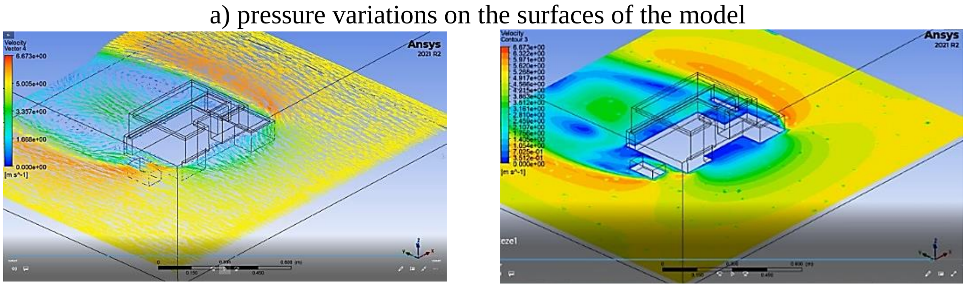


a-10) wind pressures for -10° angle of incidence

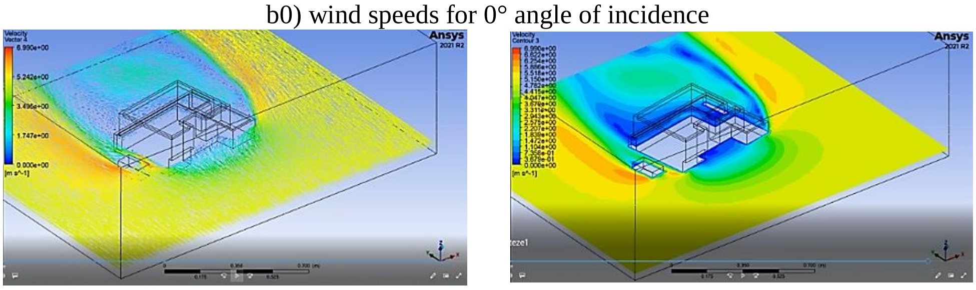


a-20) wind pressures for -20° angle of incidence

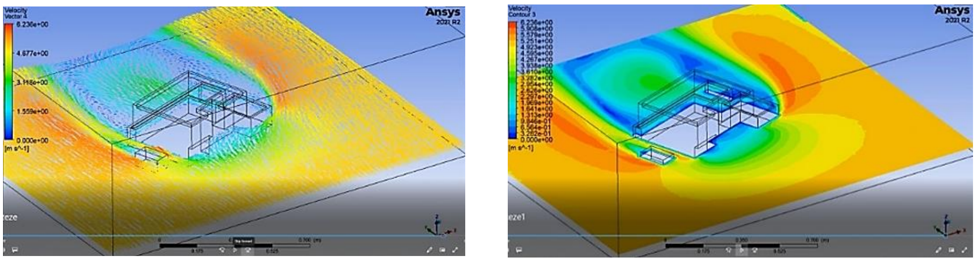
a) pressure variations on the surfaces of the model



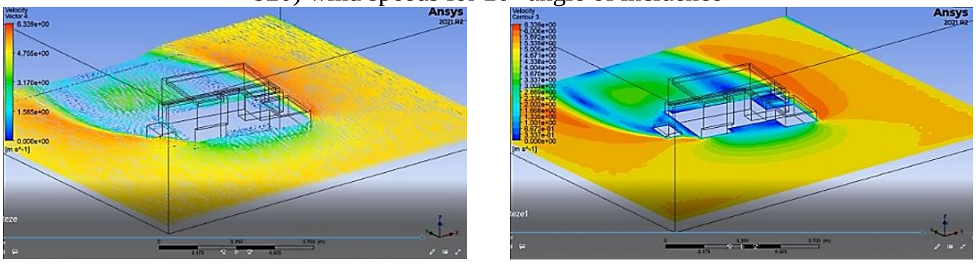
b0) wind speeds for 0° angle of incidence



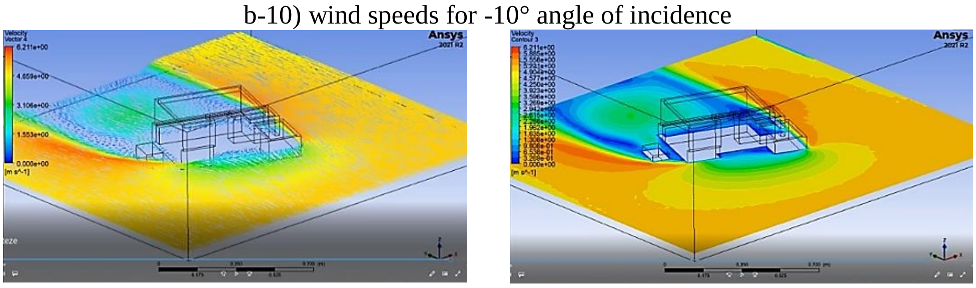
b10) wind speeds for 10° angle of incidence



b20) wind speeds for 20° angle of incidence



b-10) wind speeds for -10° angle of incidence



b-20) wind speeds for -20° angle of incidence

b) wind speeds variations around the model

Fig. 9 Model without vegetation + outdoor dining table

From the analysis of the pressure distribution across the surfaces of the model we can draw a serios of conclusions.

We can observe in the figures from a0) to a-20) that of the surfaces that are exposed to a wind speed of 5.25 m/s, pressure varies depending on the wind's angle of incidence. The variation is presented in Ttable 2.

Table 2 Pressure variation on the model surfaces according to the angle of incidence

Incidence angle	Maximal pressures	Minimal pressures
[^{o}]	[Pa]	
20	18.48	-20.47
10	18.80	-29.00
0	18.75	-19.94
-10	17.76	-20.03
-20	16.90	-16.44

The graphic representation of the pressure variation is presented in figure 10.

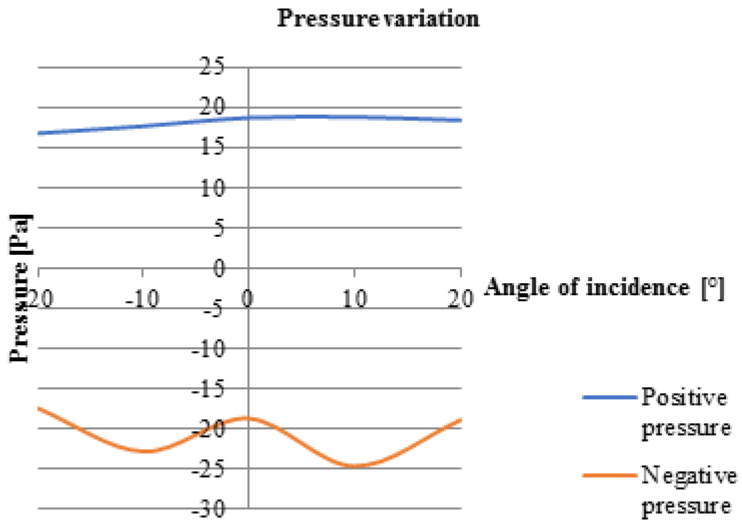


Fig. 10 Pressure variation

By analysing the pressure variation both in figure 9 and in the graphical representation of maximal and minimal pressures in figure 10 we can conclude that:

a) The most unfavourable situation is again for a 10° incidence angle. Therefore, the result remains the same as for the experiment without the outdoor dining table with the mention that discomfort is as present in the dining area as it is at the entrance in the building.

b) The most favourable direction for the wind remains at a -20° angle of incidence from the North-South orientation of the house.

c) In figure 9 a0) we notice a depression area behind what would be the dining table. Obstacles in the wind direction increase comfort in the area opposing the air circulation.

d) From analysing figure 9 a10) we notice that on the table surface that is exposed to wind high pressure occurs. This leads to the conclusion the special fixtures would be needed to cement the table against wind.

e) In figure 9 a10) we detect that for a 10° angle of incidence an air speed increase happens between the house model and the dining table. The reasons for this phenomenon are because of the presence of the corner and the narrowing of the free space.

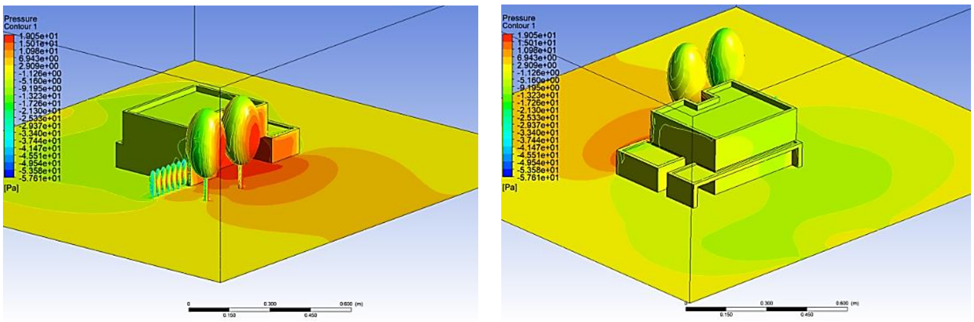
4.1.3 Model with high and low vegetation

The experiment is done once again, this time however without the outdoor dining table. Furthermore, high and low vegetation was added to the digital model. In this specific case study, we should observe the effect that their presence would have on the pressure variation and wind speeds.

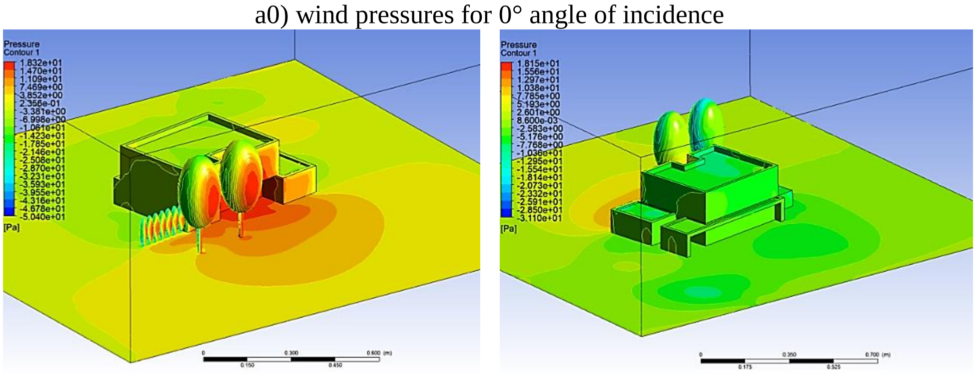
As described 2 trees with a height of 7 to 10 m were placed on the North East side of the plot. At the ground level 7 shrubs with a height on 3.5m were placed as a continuation of the house wall that would act as a wind-screen against the air flow.

For the presented situation the resulting pressure variation is shown in figure 11 a). The wind speeds changes simulations for the same case study are represented below in figure 11 b).

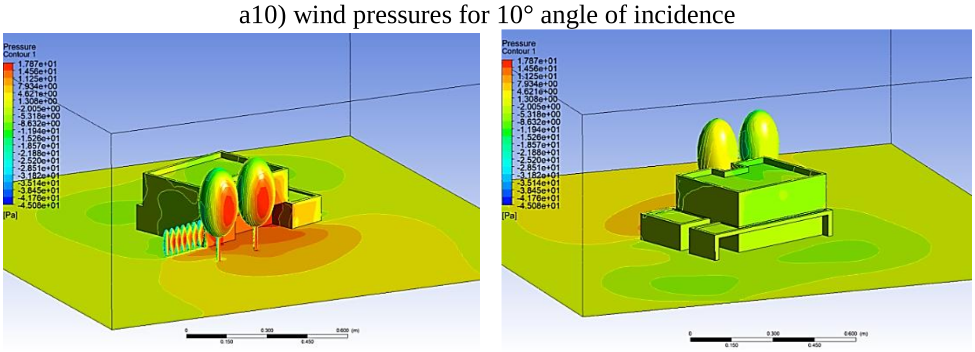
North elevation South elevation



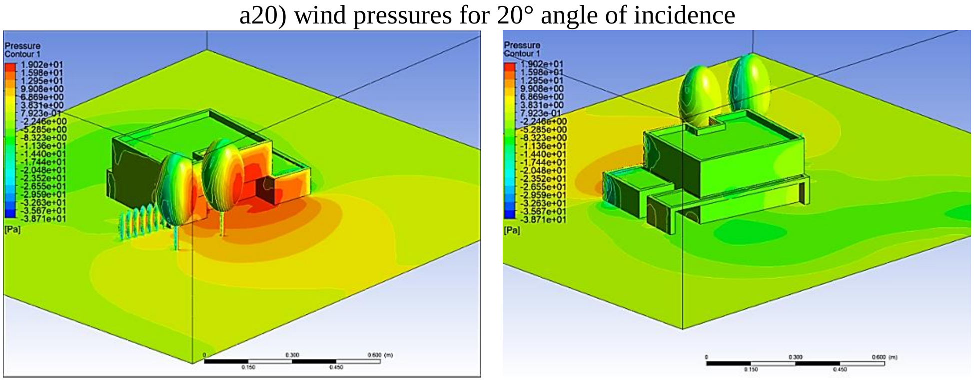
a0) wind pressures for 0° angle of incidence



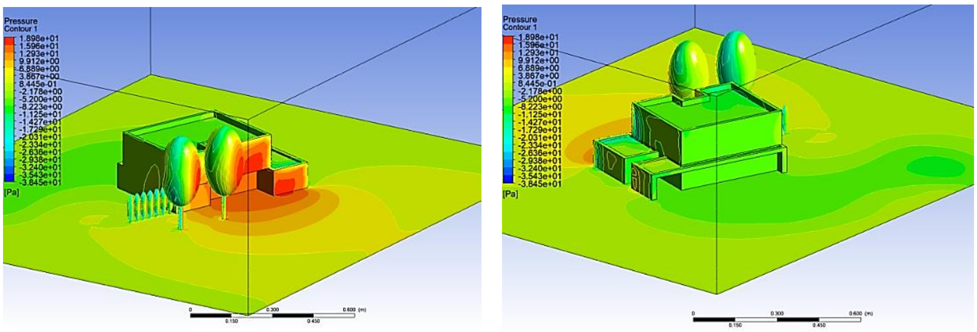
a10) wind pressures for 10° angle of incidence



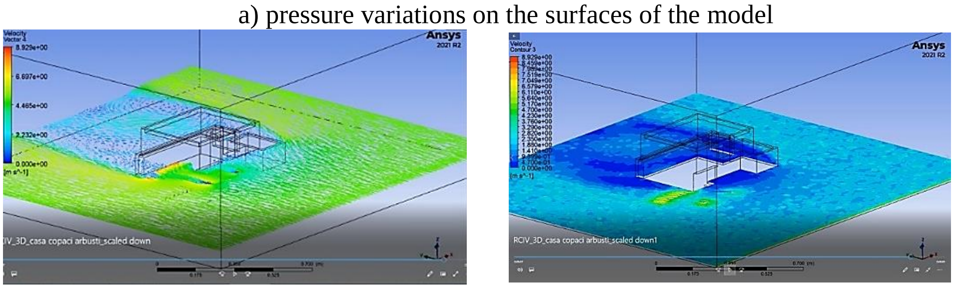
a20) wind pressures for 20° angle of incidence



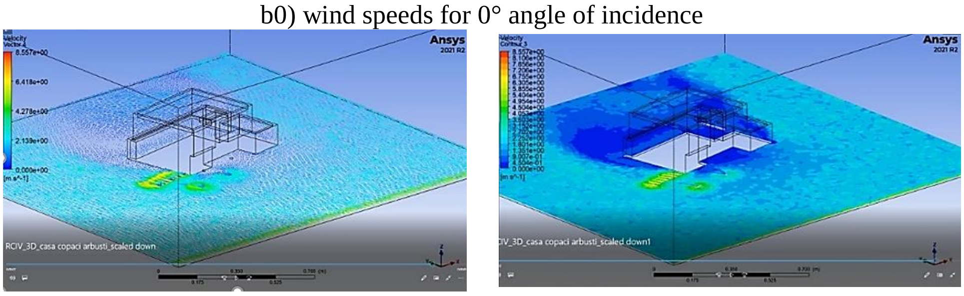
a-10) wind pressures for -10° angle of incidence



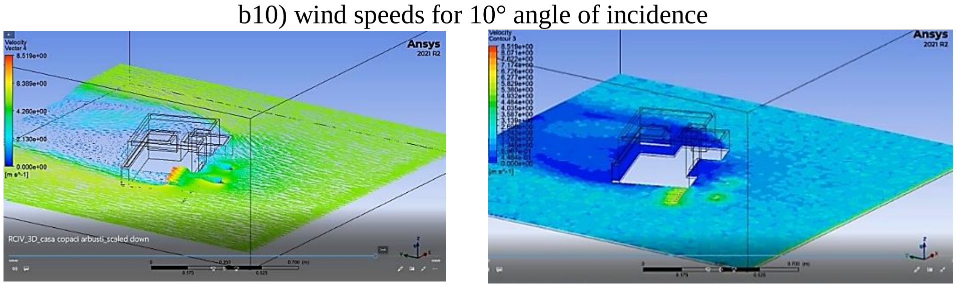
a-20) wind pressures for -20° angle of incidence
a) pressure variations on the surfaces of the model



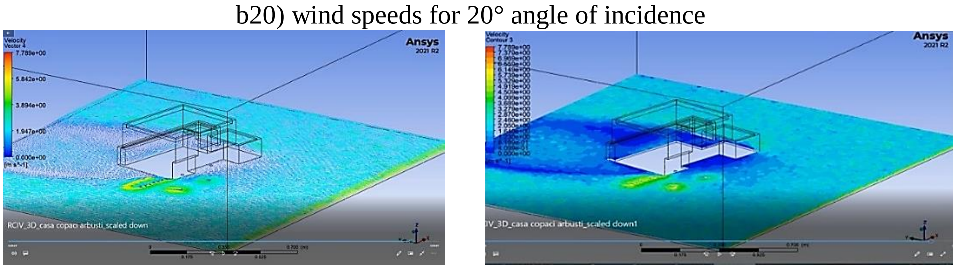
b0) wind speeds for 0° angle of incidence



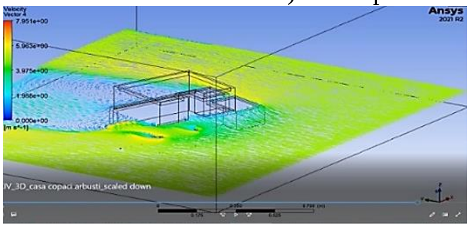
b10) wind speeds for 10° angle of incidence

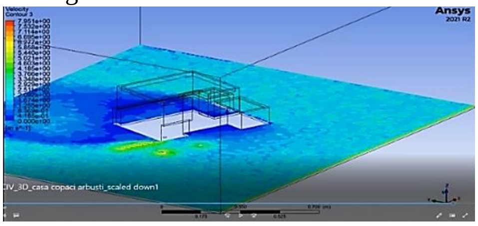


b20) wind speeds for 20° angle of incidence



b-10) wind speeds for -10° angle of incidence





b-20) wind speeds for -20° angle of incidence

b) wind speeds variations around the model

Fig. 11 Model with low and high vegetation

From the analysis of the pressure distribution on the surfaces of the model we can draw the following conclusions.

The pressure variation highly depends on the angle of incidence to the North-South orientation of the house as we can see from table 3.

Table 3 Pressure variation on the model surfaces according to the angle of incidence

Incidence angle	Maximal pressures	Minimal pressures
[°]	[Pa]	
20	17.87	-45.08
10	18.32	-50.04
0	19.05	-57.61
-10	19.02	-38.71
-20	18.98	-38.45

The graphical representation of the pressure variation can be found below in figure 12.

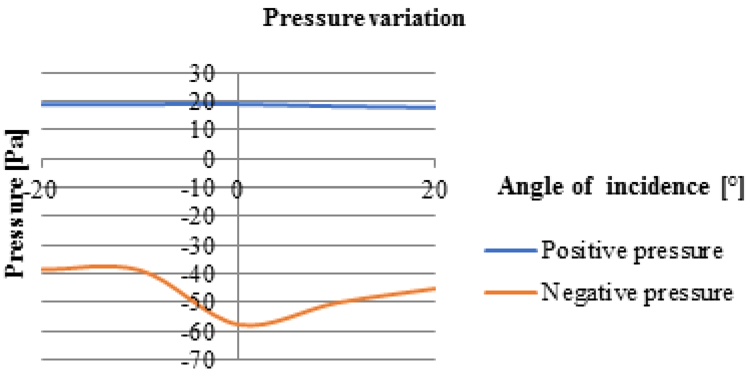


Fig. 12 Pressure variation

By analysing the pressure variation seen in figure 11 and the graphical representation of maximal and minimal pressures in figure 12 we draw the following conclusions:

a) In this specific case the most unfavourable situation is for a 0° incidence angle to the North-South orientation of the house. We notice that the presence of the vegetation alters the pattern of the air flow around the house. In comparison to the situation where we had no vegetation the pressure drops. It seems that the addition of vegetation has a positive effect on the air circulation around the individual house.

b) For both angles on incidence, 20° and -20°, the presence of the vegetation lowers the wind effects on the house and its surroundings.

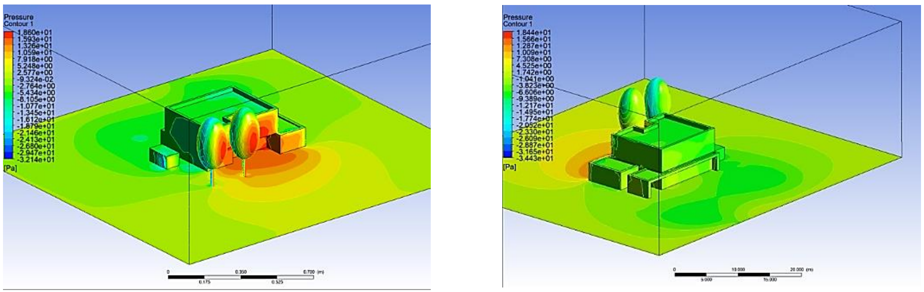
c) In figure 11 we notice that tall vegetation helps reducing the depression area on the flat roof. Consequentially the area that should be cleared of settled dust, snow or leaves is also reduced.

d) From the analysis of the wind speeds diagrams we can see an increase around the trees that is due to the shape of the trees. However overall, the air circulation speeds are below the incident one.

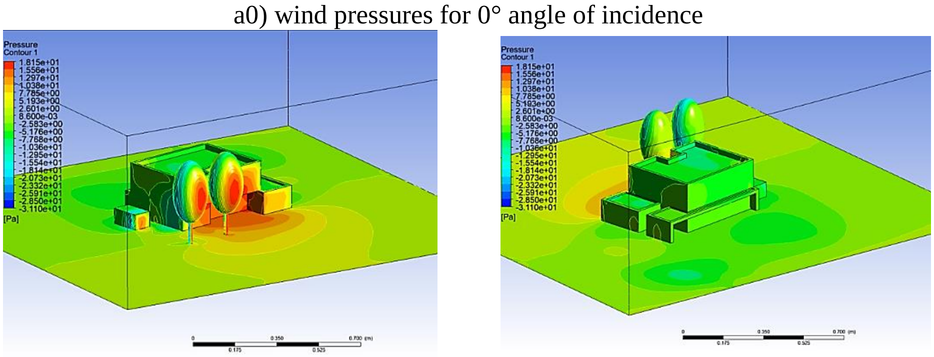
4.1.4 Model with high vegetation + outdoor dining table

The numerical projection for the proposed case study can be seen in figure 13 a). The wind speed variation around the individual house is presented in figure 13 b).

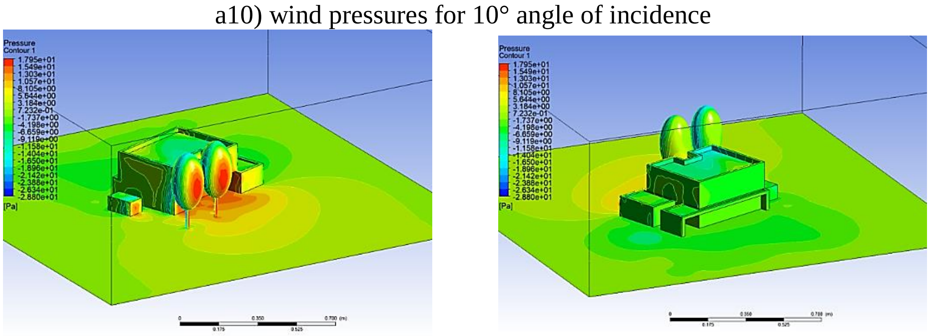
North elevation South elevation



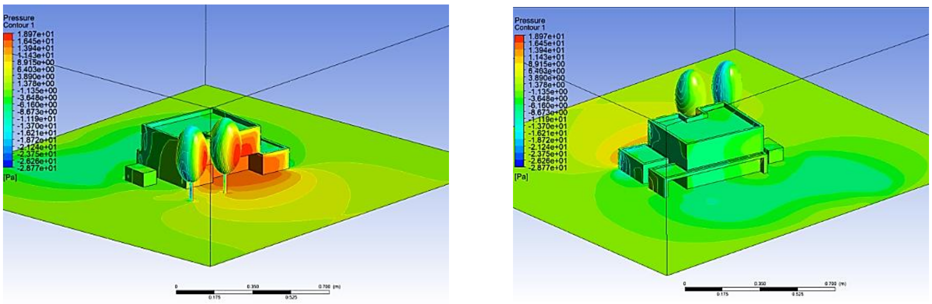
a0) wind pressures for 0° angle of incidence



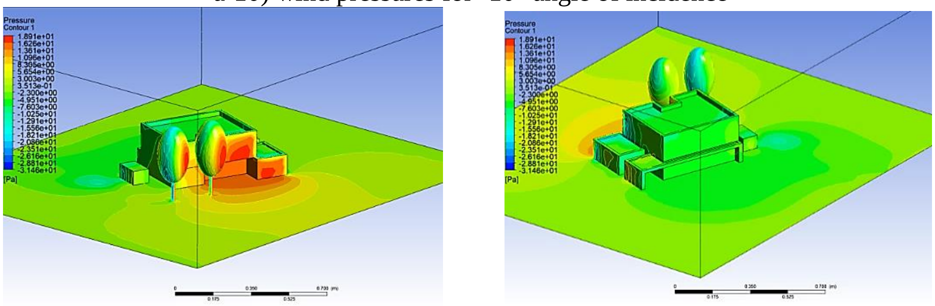
a10) wind pressures for 10° angle of incidence



a20) wind pressures for 20° angle of incidence

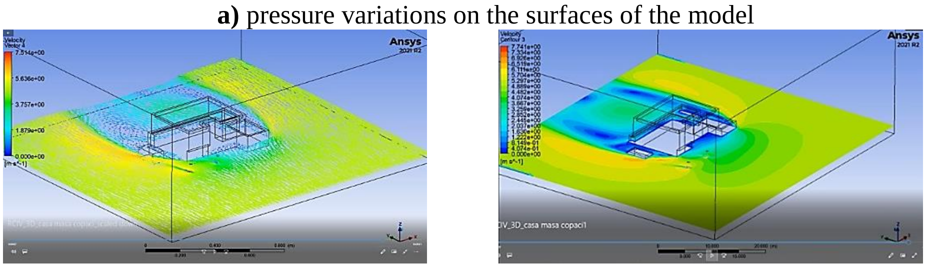


a-10) wind pressures for -10° angle of incidence

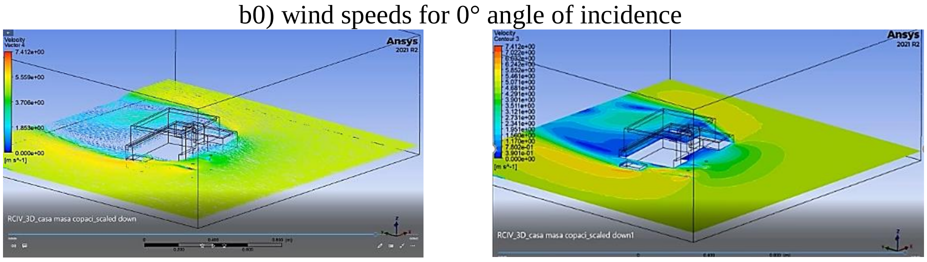


a-20) wind pressures for -20° angle of incidence

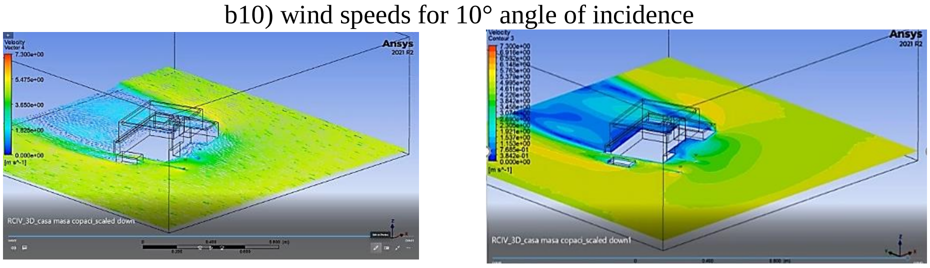
a) pressure variations on the surfaces of the model



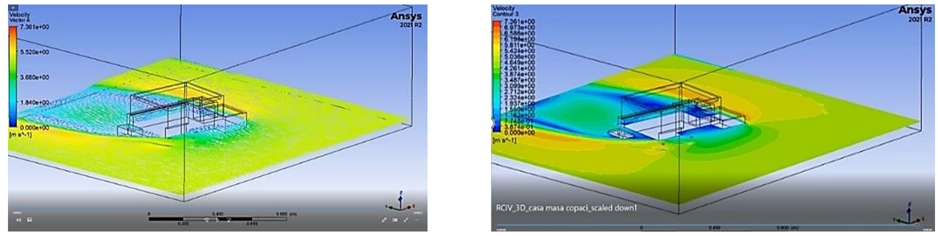
b0) wind speeds for 0° angle of incidence



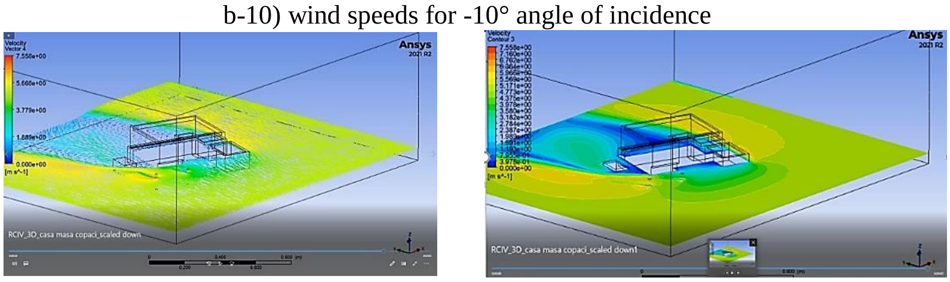
b10) wind speeds for 10° angle of incidence



b20) wind speeds for 20° angle of incidence



b-10) wind speeds for -10° angle of incidence



b-20) wind speeds for -20° angle of incidence

b) wind speeds variations around the model

Fig. 13 Model with high vegetation + outdoor dining table

From the analysis of the numerical model presented above we can draw some conclusions.

The distribution of wind pressures varies depending on the angle of incidence. The wind pressure values can be found in table 4.

Table 4 Pressure variation on the surfaces of the model according to the angle of incidence

Incidence angle	Maximal pressures	Minimal pressures
[°]	[Pa]	
20	17.95	-28.80
10	18.15	-31.10
0	18.60	-32.14
-10	18.97	-28.77
-20	18.91	-31.46

The graphical representation of the pressure distribution can be found in figure 14.

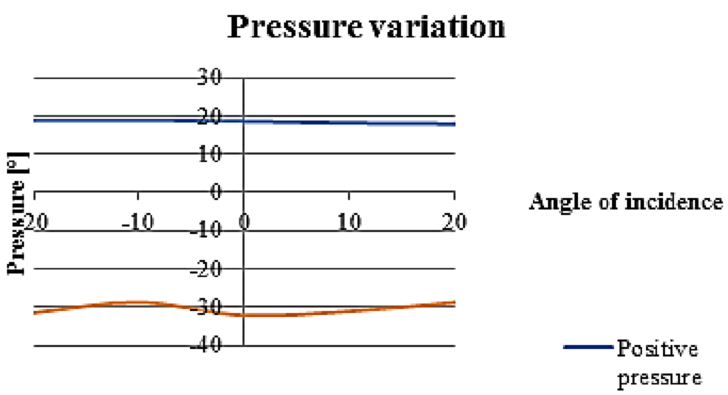


Fig. 14 Pressure variation

After the analysis of the pressure variation presented in figure 13 and the graphical representation of the minimal and maximal pressures shown in figure 14 we conclude that:

a) The 0° angle of incidence is the most detrimental one to the individual house for both negative and positive pressures. The areas where negative pressures occur are behind the trees house, on the side that is opposing the wind direction.

b) For the 10° and 20° angles of incidence the software has recorded pressures of 18.15 Pa and 17.95 Pa on the East elevation, leading to the conclusion that again, special fixtures for the table would be needed.

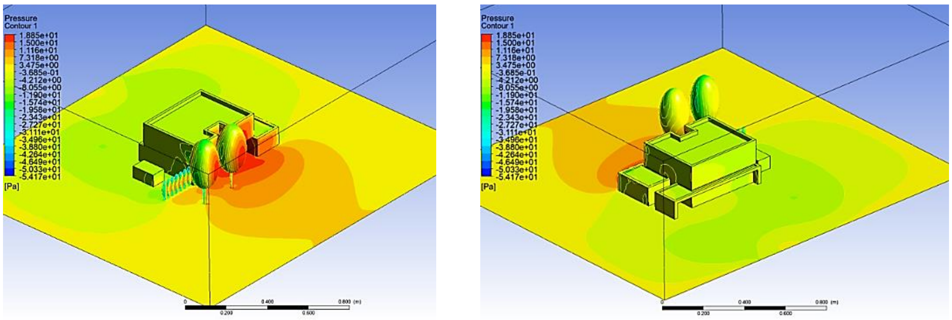
c) In figure 13, as before, we notice that the presence of vegetation reduces the depression area on the roof.

d) In the wind speed variation diagrams we observe an increase of velocity at the table level. This is a consequence of the lack of low vegetation and the presence of the high vegetation.

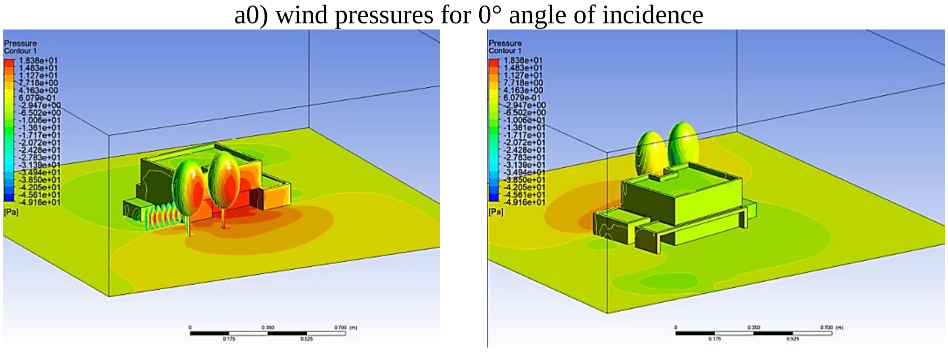
4.1.5 Model with high and low vegetation + outdoor dining table

For this case study we can see the results of the calculations for the pressure variation in figure 15 a). The changes in air circulation speed are recorded in figure 15 b).

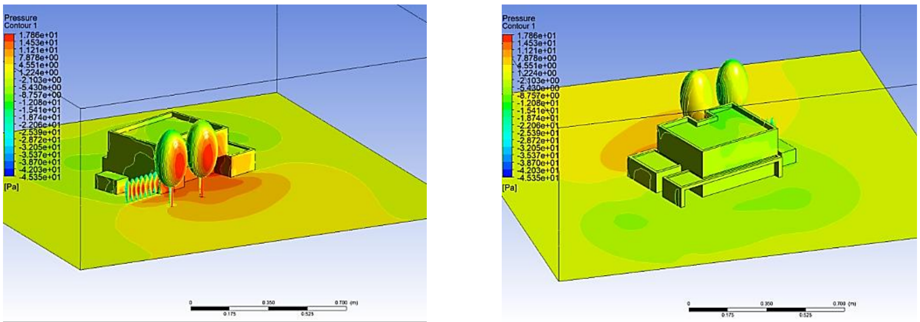
North elevation South elevation



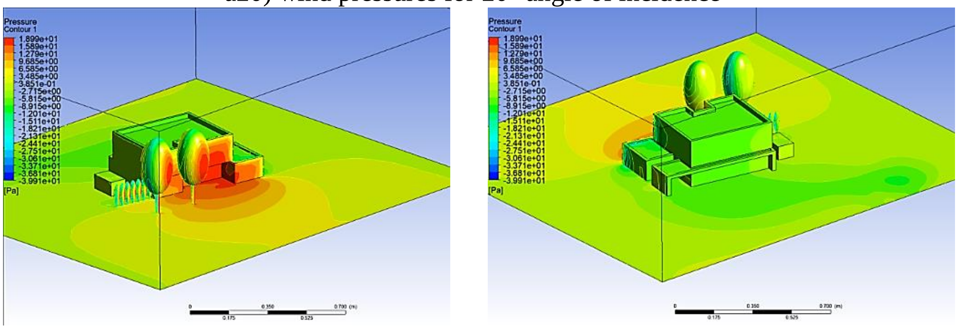
a0) wind pressures for 0° angle of incidence



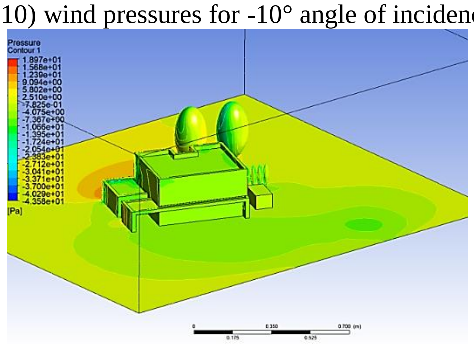
a10) wind pressures for 10° angle of incidence



a20) wind pressures for 20° angle of incidence

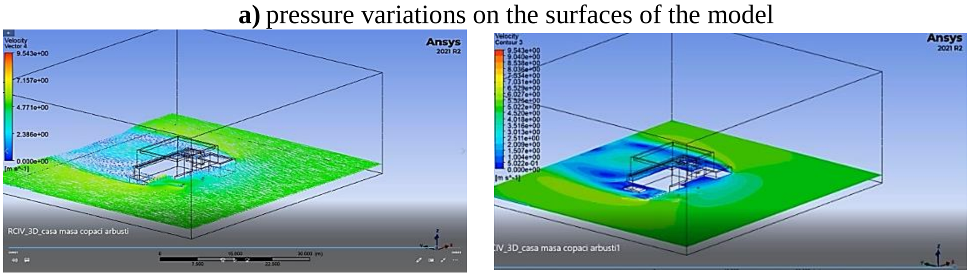


a-10) wind pressures for -10° angle of incidence

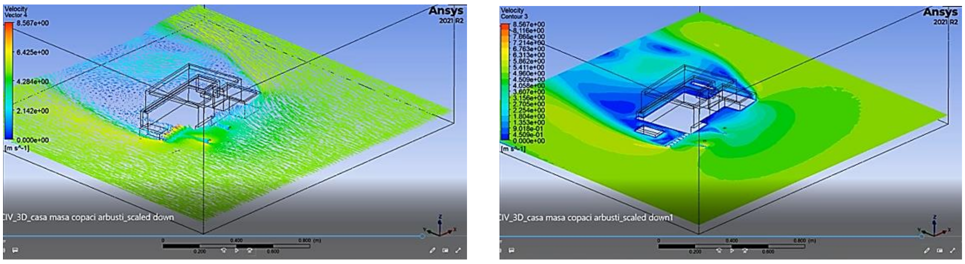


a-20) wind pressures for -20° angle of incidence

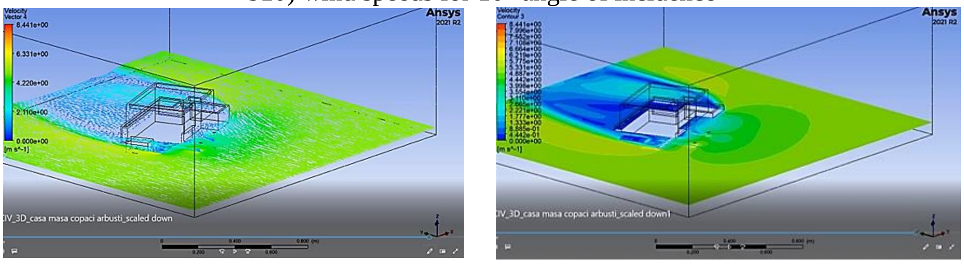
a) pressure variations on the surfaces of the model



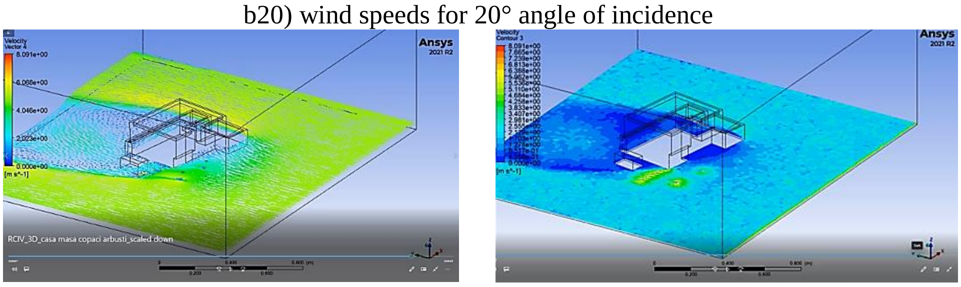
b0) wind speeds for 0° angle of incidence



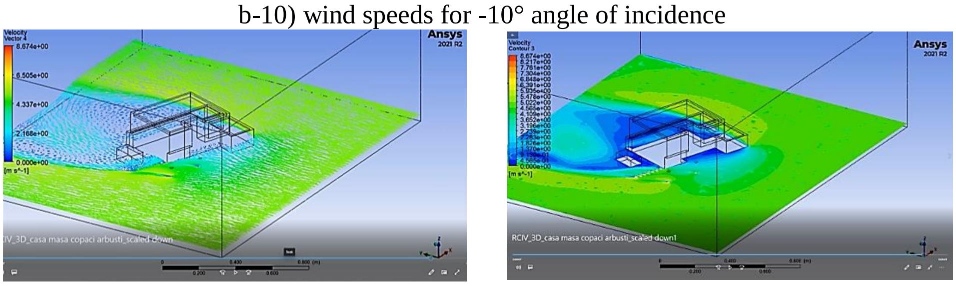
b10) wind speeds for 10° angle of incidence



b20) wind speeds for 20° angle of incidence



b-10) wind speeds for -10° angle of incidence



b-20) wind speeds for -20° angle of incidence

b) wind speeds variations around the model

Fig. 15 Model with high and low vegetation + outdoor dining table

The analysis of the pressure distribution across the surfaces of the model leads to the following conclusions.

The resulting pressures vary depending on the angle of incidence for the wind direction to the North-South orientation of the house. The pressure values are noted in Table 5.

Table 5 Pressure variation on the surfaces of the model according to the angle of incidence

Incidence angle	Maximal pressures	Minimal pressures
[°]	[Pa]	
20	17.86	-45.35
10	18.38	-49.16
0	18.85	-54.17
-10	18.89	-39.91
-20	18.97	-43.58

The graphical representation for the pressure variation is presented in figure 16.

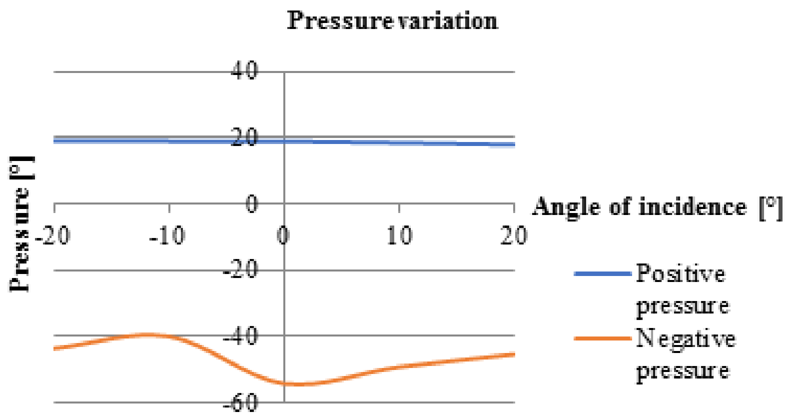


Fig. 16 Pressure variation

The analysis of both the pressures presented in figure 15 and the graphical representation in figure 16 lead to the following conclusions:

a) The least favourable situation is when the angle of incidence is of a value of -10° to the individual house orientation. Following is the 0° angle for the direction of the wind.

b) The presence of low vegetation acting as an obstacle in the way of the wind greatly reduces its effect on the surrounding area proving beneficial both to the comfort of the inhabitants and the individual house's accessories.

c) In figure 15, as with the case presented before, we notice that the placement of high vegetation reduces the depression area on the roof.

d) The analysis of the air circulation speeds proves there is an increase of velocity whenever a surface changes direction.

4.2 General conclusions

The analysis done in the previous chapters leads to the following general conclusions:

a) The presence of both high and low vegetation seems to be beneficial in the way it influences the way air flows pattern around the house. For some of the angles of incidence for the wind they prove to be a good solution for the reduction of turbulences. Even though vortices can't be completely cancelled in areas such as the entrance or the roof, they can diminish their effects while enhancing the wind resilience of the house and the comfort of the inhabitants.

b) The results provided by the software offer an insight that can be beneficial to architects and engineers from the concept stage of design. Measures can be taken in order to minimize wind turbulences and unwanted vortices that occur especially in narrow spaces and when a surface changes direction.

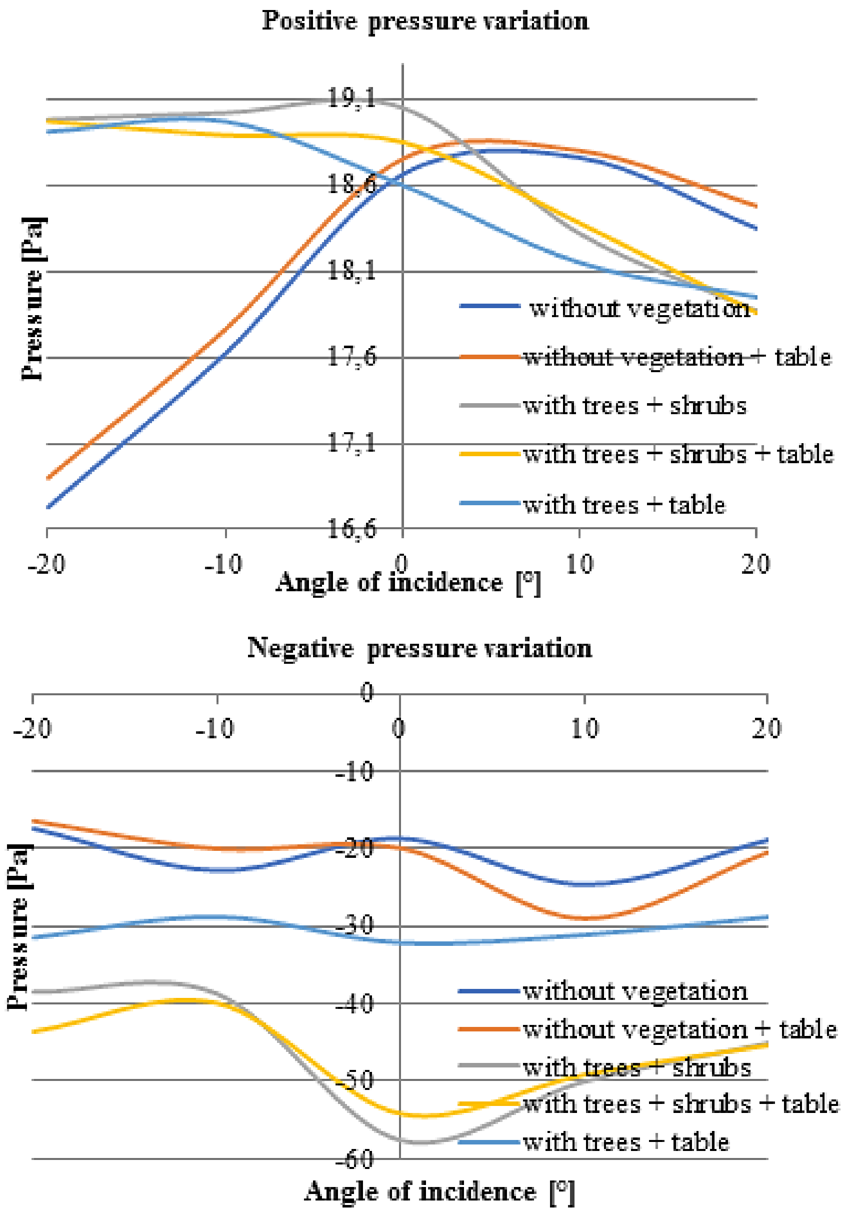


Fig. 17 Positive and negative pressure variation

c) In places where the wind pressure is characterized by high values, especially on large surfaces, special solutions can be implemented that should fragment the exposed plane in order to protect them from unwanted deterioration. These variable forces of vortices can cause destructive or uncomfortable vibrations to elements such as rain gutters, thermal insulation, window sills, and roofs.

d) In the graphs from figure 17 we have centralized the data gathered from all the case studies analysed in the previous chapter. For the positive pressures we notice that the presence on vegetation provides a solution to stop unwanted vibrations from occurring. For the negative pressures, the formation of vortices suggests that debris, dust or snow will settle. They should be studied further in order to find a solution to prevent this phenomenon from happening.

e) Numerical models, being cheaper, faster and more precise, prove to be a better solution than physical experiments. Therefore, they have been greatly adopted by professionals in many branches of production. Such analysis, implemented from the concept stage of design provide the opportunity to minimize and remedy the destructive and uncomfortable effects of wind flow patterns around different types of built structures.

f) The above presented studies can be further validated by physical experimentation conducted in wind tunnels in order to prove the efficiency of numerical methods in building design.

Following the numerical analysis done in the present study, a branch of CFD methods, provide the necessary data for the design stage of a built project, that have the possibility to reduce and cancel unwanted effects of destructive air flow patterns around buildings. It can also greatly increase the comfort of the inhabitants both inside the residential unit and during outdoor activities.

5. References

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[7]https://www.meteoblue.com/ro/vreme/historyclimate/climatemodelled/gala%C8%9Bi_rom%C3%A2nia_677697

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