Application of multicriteria optimization in wind flow analysis

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ABSTRACT: The paper presents an example of the optimization of a three - building arrangement as a function of three variables describing their alignment relation to one another. Several cases of the potential arrangement of buildings have been studied. Wind flow for different distances between buildings and for eight directions of approaching wind have been considered. The simulation process has been carried out using K-ε turbulence model. As a result of this analysis flow zones around the buildings with different levels of influence on wind comfort have been determined. The optimization of building arrangement deals with the problem of selecting the values of several variables which determine wind flow pattern. In order to provide required wind comfort and ventilation around urban complex three criteria of optimization have been applied. Computer program CAMOS (Computer Aided Multicriterion Optimization System) has been used for the optimization procedure.

Keywords: wind, multicriteria optimization, CFD simulation, comfort

1. INTRODUCTION

Wind structure adapted for the topography is subject to changes while flowing into the urban area. Land development causes the increase of ground roughness thus contributing to weakening of wind speed. Along with the increase of land development density, the difference between the average wind velocity over the city surrounding area and wind velocity within the city grows.

At the same time over the area characterized by concentration of buildings, the passing air of the lower layer of the atmosphere is forced in between the bodies of the buildings, thus causing the interference of the wind with local turbulences produced by the building bodies themselves. In some situations it leads to the creation of zones characterized by high wind speed and vortices.

There is a large number of flow parameters including building geometry, wind speed and wind direction, roughness parameters and thermal parameters. Additional difficulty is caused by randomness in wind direction and speed.

In order to create comfortable conditions for the inhabitants, architects and urban planners have to consider many aspects, very often contradictory ones. Efficient ventilation is necessary to maintain clean atmosphere and to protect city centers from overheating of city centres during hot summers, on the other hand, too strong wind flow can affect pedestrian comfort. It is necessary to reach a compromise. Finding an optimal building arrangement requires studying a great number of cases and considering many influencing factors.

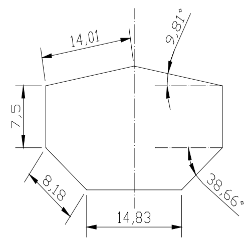
Computational Fluid Dynamics (CFD) software is increasingly being used to predict wind effects on buildings and on people in urban environment. It is a useful method of wind environment assessment in a case when we have to analyse many examples of building arrangement in relatively short period of time. Since it is necessary to take into account many factors shaping the wind flow optimization method should be used. Application of both numerical simulations together with multicriteria optimization seems to be a promising method.

2. BUILDING ARRANGEMENT EFFECT ON WIND VELOCITY

The analysed complex consists of three buildings: one building of the “B” type of 8.4m height and two “A” type buildings of 8.4m height. Shapes and dimensions of both types are presented in (Fig.1). The assumed buildings shape and dimensions are the result of previous optimization analysis [1][2].

The first step in multicriteria optimization procedure was the numerical simulation of wind flow around the buildings. The simulations have been done for 27 variants of building arrangement and 8 wind directions.

On the basis of 10-year meteorological data the initial wind speed V = 5m/s (at an altitude of 10m above the ground level) has been assumed. It is worth noting that the frequency of that velocity occurrence yields to changes according to wind directions, North 17%, North/East 18%, East 15%, South/East 11%, South 19%, South/West 14%, West 14% and North/West 16% (Fig.2). The above fact was considered while solving the optimisation task.



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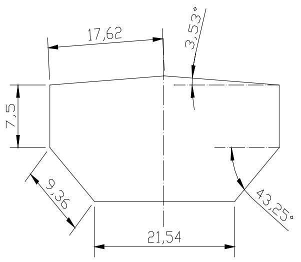

Type “B”

Figure 1: Shapes and dimensions of „A” and „B” buildings

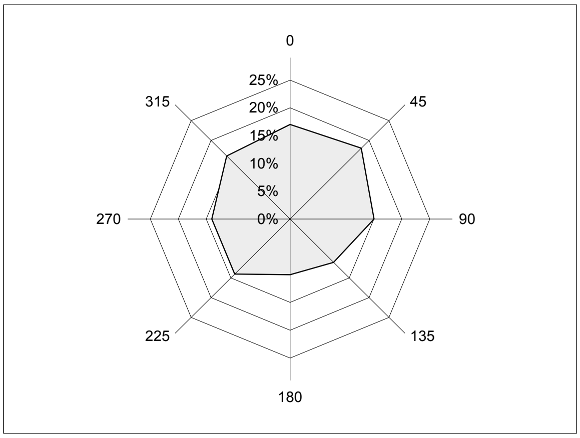

Figure 2: Distribution of 5 m/sec velocity occurrence in percentages

The frequencies of wind occurrence from different directions are as fallows: North 8%, North/East 6%, East 12%, South/East 15%, South 12%, South/West 12%, West 25% and North/West 10%

The numerical analysis of wind flow around analysed buildings has been developed with the aid of the standard k – ε model proposed by Launder and Spalding [3]. The governing equations were the time-averaged, momentum, continuity, and the k – ε model equations [4]. Taking into account the updated Davenport classification [5] roughness length z_o for inflow has been assumed at 0.25 m (for rural area). Building roughness was taken as 0.002 m. In the inlet of the computation domain logarithmic mean wind profile, including change of the roughness parameters, has been established as well as kinetic energy profile and dissipation rate profile [6]. The dimensions of the computational domain were W,L,H = 240 x 190 x 84 m. Unstructured tetrahedral grid has been generated with a total of over 1 million cells. A higher mesh density has been defined in the vicinity of the buildings.

As a result of the above analysis, flow zones around the buildings with different levels of influence on wind comfort have been obtained. As the pedestrian comfort was crucial the analysis has been conducted for the 1.8m height. Figures 3 – 6 shows examples of wind speed patterns.

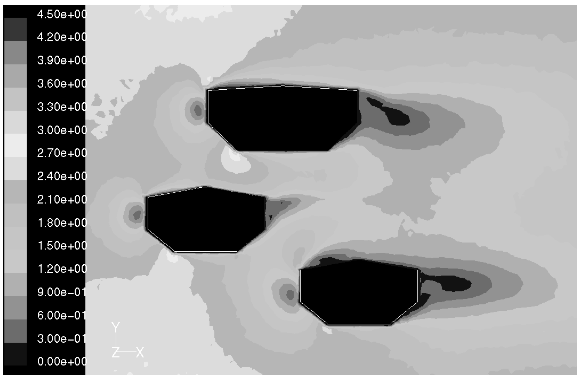

Figure 3: The wind speed areas – west wind direction

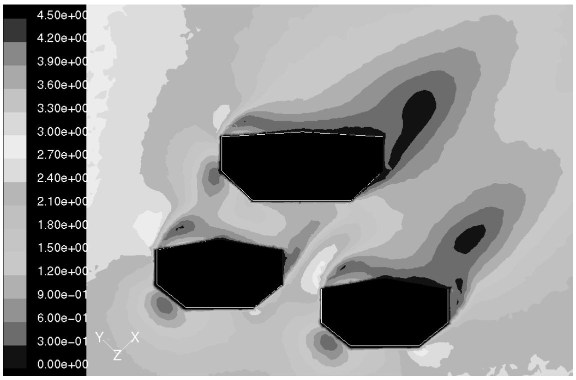

Figure 4: The wind speed areas – south – west wind direction

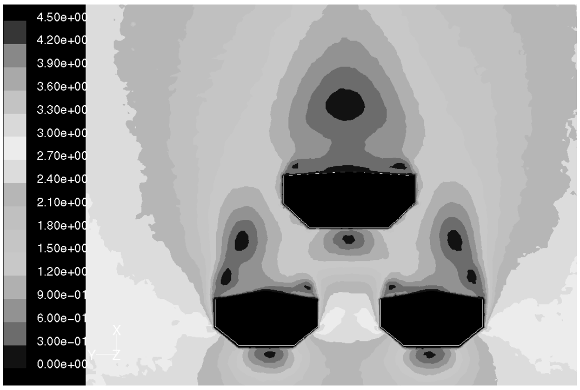

Figure 5: The wind speed areas – south wind direction

Figure 6: The wind speed areas – north – west wind direction

3. OPTIMIZATION OF THE BUILDINGS ARRANGEMENT

3.1 Formulation of the problem

For the purpose of the study three impact zones have been taken:

- the zone with wind velocity intervals from 0 to 1 m/s; the above case is unfavourable due to aero-sanitary and bio-climatic conditions; it is connected with the so-called atmospheric calm occurrence,
- the zone with wind velocity intervals from 1 to 5 m/s; this case is favourable since that range of velocity provides air exchange and certain wind comfort,
- the zone with wind velocity intervals from 3 to 6 m/s; in this velocity interval air exchange (ventilation) is provided.

As it follows from the cited data, while pursuing a favourable building arrangement, due to the development of zones of different size, it is necessary to reach a certain compromise between maintaining a mutual proportion of zones in which wind comfort conditions are met and the size of zones providing good ventilation conditions.

The choice of the above zones resulted mainly from adopting the initial velocity of 5 m/s to the simulation analysis. In the case of adopting a higher initial velocity, e.g. 10 m/s, where wind velocity would reach a limit from 6 to 10 m/s, a zone of wind discomfort should be additionally considered. Pedestrians movements within such a zone would be hampered, whereas favourable ventilation conditions would prevail.

The choice of an optimal mutual arrangement of the buildings requires to determining areas of surface of the three flow zones with wind velocity at the altitude of 1,8 m reaching the values in the intervals 0 – 1 m/s, 1 – 5 m/s, 3 – 6 m/s. These areas have been determined for different wind directions successively for each variant of building arrangement, disregarding mirror situations.

In purpose of considering the fact that the adopted initial velocity of 5 m/s occurs in varied probability for successive azimuth, after the size of the above mentioned zones have been determined, weight factors presented in (Fig. 7). have been defined [7].

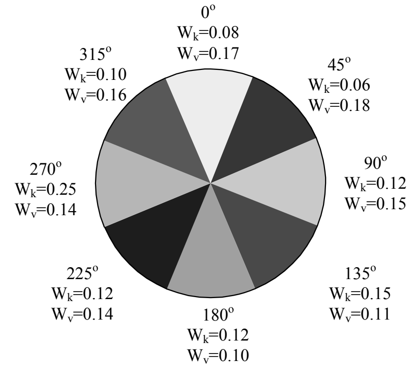

Figure 7: Weight factors related to direction W_k and wind velocity W_v

In order to solve the optimization task, quantities being a ratio of the surface area of the flow zone intervals: 0 – 1 m/s, 1 – 5 m/s, 3 – 6 m/s, to the surface area in which significant distortions of wind velocity occur in the vicinity of the investigated group of buildings, influential to the general picture of flows, have been assumed. Weight factors related to wind direction and velocity have been also considered. The distribution of velocities has been analysed at an altitude of 1,8 m above ground level.

The objective function has been thus defined as following:

$$F = \frac{\sum_{n=1}^{N} S^{n}_{(z_1,z_2)} W_k^n W_v^n}{NS_0}, \tag{1}$$

where:

$S^n_{(z_1,z_2)}$ - the surface area of the zone with the velocity of wind blowing from the n direction includes in the interval (z_1, z_2), m^2,

W_k^n - the weight factor related to the n direction wind occurrence frequency, (Fig. 7)

W_v^n - the weight factor related to the wind velocity of 5 m/s occurrence frequency, (Fig.7),

S_0 - the surface area of the terrain where significant wind velocity distortions caused by the buildings occur, m^2,

N – number of analysed wind directions.

As the optimisation criteria have been assumed:

- the minimum of F function, wind velocity interval 0 - 1 m/s,

$$F_1 = \frac{\sum_{n=1}^{N} S^{n}_{0\div 1} W_k^n W_v^n}{NS_0}, \tag{2}$$

- the maximum of F function, wind velocity interval 1 – 5 m/s,

$$F_2 = \frac{\sum_{n=1}^{N} S_{1\div5}^{n} W_k^n W_v^n}{NS_0}, \tag{3}$$

- the maximum of F function, wind velocity interval 3 – 6 m/s,

$$F_3 = \frac{\sum_{n=1}^{N} S_{3\div6}^{n} W_k^n W_v^n}{NS_0},$$

(4)

The coordinates determining the arrangement of the buildings over the considered area x_1, x_2, x_3, are decisive variables of the objective (Fig.8). While the position of the buildings according to the cardinal points has been determined at the optimisation of the shape of the buildings.

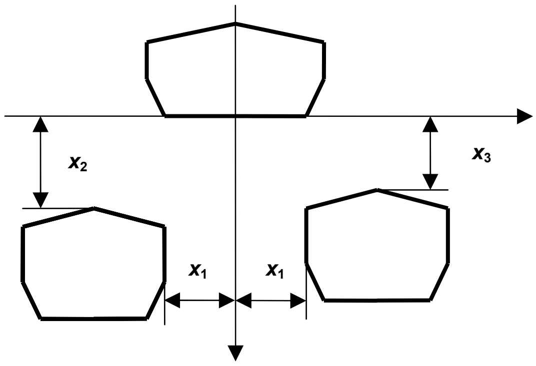

Figure 8: Graphical interpretation of the decisive variables x_1, x_2, x_3.

The decisive variables have to meet the following inequality limitations:

$$4.2 \le x_1 \le 12.6,$$
$$8.4 \le x_2 \le 25.2,$$
$$8.4 \le x_3 \le 25.2.$$

The forms of the objective function have been analytically found by approximation data determined thanks to the simulation analysis with polynomials of the second grade in the form of Eq. (5)

$$F_1(x_1,x_2,x_3) = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_1^2 + a_5x_2^2 + a_6x_3^2$$
$$+ a_7x_1x_2 + a_8x_1x_3 + a_9x_2x_3$$
$$F_2(x_1,x_2,x_3) = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_1^2 + b_5x_2^2 + b_6x_3^2$$
$$+ b_7x_1x_2 + b_8x_1x_3 + b_9x_2x_3$$
$$F_3(x_1,x_2,x_3) = c_0 + c_1x_1 + c_2x_2 + c_3x_3 + c_4x_1^2 + c_5x_2^2 \tag{5}$$
$$+ c_6x_3^2 + c_7x_1x_2 + c_8x_1x_3 + c_9x_2x_3$$

The coefficients of those equations have been defined by the least square method and presented in Table 1.

Table 1: Values of the coefficients

Subscript	Coefficients		
	a	b	c
0	0.00211075	0.0138016	0.000253078
1	0.0000190476	0.0000245146	$-4.57804\cdot10^{-6}$
2	-0.0000237593	0.0000238578	$-8.6336\cdot10^{-6}$
3	-0.0000299319	0.0000246177	$-6.72024\cdot10^{-6}$
4	$-8.12862\cdot10^{-7}$	$-1.77343\cdot10^{-6}$	$1.22827\cdot10^{-7}$
5	$3.80685\cdot10^{-7}$	$-5.64531\cdot10^{-8}$	$3.56198\cdot10^{-7}$
6	$5.07291\cdot10^{-7}$	$-1.85185\cdot10^{-7}$	$2.74471\cdot10^{-7}$
7	$-1.16922\cdot10^{-7}$	$1.10544\cdot10^{-7}$	$2.03137\cdot10^{-8}$
8	$-4.0155\cdot10^{-8}$	$3.63757\cdot10^{-8}$	$7.39324\cdot10^{-8}$
9	$3.01398\cdot10^{-7}$	$-7.89163\cdot10^{-7}$	$-1.13142\cdot10^{-7}$

Thanks to this, an ideal solution, a set of nondominated solutions, and a preferable solution can be numerically found with the use of the CAMOS packet [8].

After a set of compromises is found, with the help of e.g. the mini-max method with the weight factors, the normalized objective functions have been determined:

$$\Phi_1 = \frac{F_1}{\overline{F_1}},$$
$$\Phi_2 = \frac{F_2}{\overline{F_2}}, \tag{6}$$
$$\Phi_3 = \frac{F_3}{\overline{F_3}}$$

With $\overline{F_1}, \overline{F_2}\,\mathrm{and}\,\overline{F_3}$, the highest values of $F_1(x)$, $F_2(x)$ and $F_3(x)$, belonging to the set of compromises, have been marked. The next step is to determine the set of compromises within the normalized space of the objective function. A preferable solution may be defined as a point belonging to the set of compromises, closest to the ideal point. The preferable arrangement of buildings within the groups under consideration has been defined in that way.

3.2 Solution of the optimization problem

The solution of the problem has been found numerically by applying the CAMOS packet software [8].

The ideal solution is the following:

F_1^{ID} =0.001555507; F_2^{ID} =0.0145059; F_3^{ID} =0.00018838,

while:

$\overline{F_1}$ =0.001653805; $\overline{F_2}$ =0.01447826; $\overline{F_3}$ =0.0001659524.

In accordance with the Eq.(6), in purpose of finding the set of compromises and a preferable solution, nondimensional normalized objective function has been introduced.

The calculations have been repeated, thus obtaining coordinates of the ideal point in the nondimensional space of objectives:

Φ_1^{ID} =0.9405624; Φ_2^{ID} =0.9999998; Φ_3^{ID} = 1.000000.

The point of the set of compromises, closest to the ideal point in the nondimensional space of objectives function, has been assumed as a preferable solution. Its coordinates are as follows:

Φ_1^{pr} =0.9518112; Φ_2^{pr} =0.9956295; Φ_3^{pr} = 0.9903267,

and the decisive variables take on values:

$x_1 = 12.6$; $x_2 = 25.2$; $x_3 = 25.2$.

4. CONCLUSION

In the recent years strong public interest in the quality of urban environment and energy-savings can be observed. Creation of the comfortable environment becomes one of the essential tasks. The outdoor comfort is affected by many parameters like solar energy, ventilation, lighting, noise and also by visual effects. Due to it's complexity and variability designing of the human-friendly and comfortable cities is very difficult process. Optimisation methods allow to consider many aspects very often contradictory. As a result of the optimisation process we can obtain for example an optimal land development or energy - saving buildings.

The application of the numerical modelling in the analysis of air flow around buildings enables optimization of the building arrangement regarding the wind criteria. Buildings located in a small distance to each other weaken ventilation process. In some situations local stagnation zones can appear. These areas are characterised by reduced air quality and snow accumulation. On the other hands in the dense urban structures local zones with high wind speed and vortices affected pedestrian comfort. In order to provide required wind comfort and appropriate ventilation around analysed buildings three criteria of optimisation have been applied – minimum of area with wind speeds between 0–1m/s and maximum area with wind speeds 1-5m/s and 3–6m/s. The solution of optimization process indicates that the following values of decisive variables: $x_1 = 12.6$; $x_2 = 25.2$; $x_3 = 25.2$, satisfy the above requirements for the specified climatic conditions. Wind comfort criteria force a separation of the buildings. Thus, the most desirable arrangement can be obtained if the second row of the buildings is parallel and positioned within the distance equal to three heights of the buildings.

In the case of assuming higher initial velocity, e.g. 10 m/s, the zone of wind discomfort should be additionally considered, where wind velocity would reach the limits of from 6 to 10m/s. Pedestrians movements would be hampered in such a zone, while ventilation conditions would still be favourable

REFERENCES

[1] H. Jedrzejuk and W. Marks, Evolutional optimization of energy-saving buildings, Arch. of Civil Engineering, LI, 3, (2005), 395 – 413

[2] H. Jedrzejuk, The optimisation of residential districts, Engineering Studies, Nr. 54, (2006),

[3] B.E. Launder and D.B. Spalding, The numerical computation of turbulent flows, Computer Methods in Applied Mechanics and Engineering 3, (1974), 269.

[4] FLUENT 6.1., User's Guide,

[5] J. Wieringa, Updating the Davenport roughness classification, Journal of Wind Engineering and Industrial Aerodynamics, 41-44, (1992), 357

[6] K. Klemm, M. Jablonski, Effect of windbreak on the wind flow in a small existing urban structure, Proc. Second International Building Physics Conference, Leuven (2003), 973.

[7] K. Klemm, Wind conditions in selected urban structures, and the choice of optimal solutions, PhD. thesis, the Technical University of Lodz, (1998)

[8] A. Osyczka Computer Aided Multicriterion Optimization System (CAMOS), International Software Publisher, Krakow, (1992)