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The Impact of 3D Building Model Detailing on Wind Comfort Simulation

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The Impact of 3D Building Model Detailing on Wind Comfort Simulation

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1. Introduction

When designing urban infrastructure, it is necessary to take a comprehensive approach to the assessment of wind effects considering not only the impact of wind flow on structural elements (buildings), but also the extent to which the urban development will affect the change of air flow in the formation of the aeration regime of the territory, as these conditions will determine the level of pedestrian wind comfort space of the urban environment [1-2].

As a result of the air flow around the urban development, various wind effects are formed, which are also caused by the mutual influence of buildings in relation to each other. Wind can be perceived differently in different natural climatic zones and at different seasons of the year. In cities characterized by low winter temperatures, it worsens unfavorable weather, while in hot summer conditions wind improves the microclimate of the territory [3-4]. Aeration mode streetss, highways, as well as cleaning the urban air basin from traffic and industrial pollutants together are the most important functions of wind in a modern city [5-6]. For several decades, computational fluid dynamics has been the main alternative tool that provides the opportunity to solve problems related to the study of level of pedestrian wind comfort [7-8].

Currently, the method of turbulence simulation based on the Reynolds-averaged Navier–Stokes (RANS) equations has gained particular popularity for studying the level of pedestrian wind comfort in urban areas [9]. However, the validity of the numerical results obtained is quite questionable. Correct simulation of wind comfort conditions can only be achieved if the behavior of turbulent flows is adequately predicted. As a rule, microscale meteorological models used for this class of problems are verified considering massing models of buildings in wind tunnels, where wind loads close to real environmental conditions are reproduced [10-12], and the objects of study simulate the shape and form of buildings and urban neighborhoods. The next stage is the transition from the study of massing models of buildings to real object models, taking into account the climatic characteristics of the environment [13-14]. Such studies necessitate meteorological data, which can be obtained through field studies [15]. This approach was exemplified in the work of Zhen Peng, Yihua Chen et al., wherein the authors conducted experimental and numerical studies of aeration regime formation in wintertime in high-rise complexes of a coastal city in Northern China. The authors employed field survey methods, monitoring data, and computational fluid dynamics methods in their work [16]. In their work, Bo Wang et al. utilized field survey data from Tianjia [17], where a neighborhood situated in the western part of Changchun and encompassed by several urban parks. This area location selected as a representative area. The meteorological data employed for the study of Changchun city was obtained from Chinese Standard Weather Database (CSWD). In the course of the research, data on the conditions of the outdoor wind and thermal comfort level in the area under consideration were obtained. Similar studies are also presented in [2, 18-19] where field and numerical research methods were employed for microclimate assessment. It is noteworthy that in the presented works, there was no quantitative comparison of numerical study data with field observations at the monitoring point. Instead, the general aeration regime was compared by means velocity values.

At present, to solve the considered class of problems, the research team of the Siberian Federal University in cooperation with the Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences has developed SigmaEco software module based on the previously developed SigmaFlow software complex [20-21]. The microscale mathematical model implemented in the presented module was subjected to rigorous validation through numerical and experimental studies. In [22], the numerical results of the model were compared with experimental data for wind flow around both single study objects and a set of objects simulating urban development. The obtained results have demonstrated a good agreement with the experimental data, particularly in terms of velocity values, which previous authors of the test models were unable to achieve when reproducing the flow with their numerical approaches [23]. In general, the numerical algorithm implemented in the SigmaEco software module allows for the adequate reproduction of physical processes related to the wind flow mechanics. This enables the prediction of wind comfort conditions in urban environments.

This paper presents the validation and validation of the developed software module. The campus of Perm State University (PSU) was selected as a representative territory.

The experience of computational studies indicated that the geometric and architectural representation of the study object affects the quantitative characteristics of flow aerodynamics [24-25], which in turn influences the determination of the pedestrian wind comfort conditions. In this regard, this paper presents the results of a comprehensive study, which involves the validation of the microscale mathematical model using field data, validation of the proposed numerical algorithms using a real quarter of the urban environment, and determining the second comfort level in the pedestrian zone. Finally, the study examined how the geometric similarity of buildings, pedestrian crossover bridges, and urban infrastructure affects the quality of numerical simulation results.

Overview of criteria for assessing the impact of the external urban environment on level of pedestrian wind comfort

The evaluation criteria permit the determination of the degree of wind impact on humans, as well as the formation of different wind zones and the characterization of these zones by wind comfort levels. The development of these criteria is based on the determination of wind intensity and strength in the street spaces of urban neighborhoods [26-27].

It is postulated that the initial wind comfort criteria were formulated in the 1960s, as a consequence of the modification of the Beaufort scale, which was originally devised for the visual assessment of wind strength at the sea surface. Subsequently, it was adapted to the external environmental conditions on the ground surface. The scale was designed to provide approximate estimates of wind speeds based on the strength of the impact, which was estimated through various signs (such as changes in the trajectory of smoke; by the nature of the behavior of leaves on trees, etc.) [28].

In the 1970s, a comprehensive study was conducted to assess the level of pedestrian wind comfort. The criteria were derived from wind speed measurements conducted within the city in various urban neighborhoods [7, 29-31]. Following data processing, minimum, maximum, and peak values were identified, which served the basis for developing criteria. Penwarden and Wise [32-33] conducted research on wind speed analysis in residential neighborhoods and determined that the threshold speed at which a person begins to feel slight discomfort is 5 m/s. Isyumov and Davenport (Isyumov, 1975), based on the results of their own research and focusing also on the Beaufort scale, determined that speeds up to 9 m/s are comfortable for being on the street.

Lawson and Penwarden [34] expanded the Beaufort scale to include peak wind gusts. When calculating average speeds, they found that in walking areas the wind speed is usually 7.9 m/s. Uncomfortable conditions are found at 13.8 m/s, and speeds above 23.7 m/s are considered extremely dangerous.

Melbourne and Joubert [35] demonstrated that the formation of wind comfort levels is directly related to various wind effects and proposed equations for determining threshold (U = 3σU > 15 m/s) and dangerous (U = 3σU > 20 m/s) velocity values. However, Ratcliff and Peterka, in the course of their study on the reliability of the developed criteria, determined that according to feedback from architects and engineers, the comfort criteria proposed by Melbourne and Joubert are inadequate for use in design [36]. This is due to the fact that it is impossible to utilize a single type of wind comfort criteria to their fullest extent, given the paucity of experimental data available. The criteria currently in use have a regional character and are therefore unable to reflect the true pattern observed in the other territory, given its diverse natural and climatic characteristics.

Within the framework of the European Concerted Action COST C14 "Impact of wind and Storm on City Life and Built Environment", the working group has conducted a comparative evaluation of the methods employed throughout Europe to assess the pedestrian wind comfort level in urban environments. The results of the studies have enabled the identification of common comfort criteria, as well as the adjustment of criteria used in different institutions.

Despite the active development of different approaches, there is no universally accepted regulation in the Eurocode for the management of wind impacts on pedestrians in urban street environments. In 2006, a wind nuisance national standard for the regulation of wind comfort in built environments (NEN 8100) was introduced. This standard defines a threshold wind speed of 5 m/s for all kinds of activity. Comfort conditions are defined according to five comfort classes ranging from A to E [37]. Table 1 presents the developed comfort criteria in chronological order.

Table 1. Wind comfort criteria in urban development [29-37].

Wind comfort criteria		Lawson, Penwarden	Penwarden, Wise	Lsyumov, Davenport	Hunt, Poulton, Mumford	Melbourne and Joubert	NEN 8100
Year		1972	1975	1975	1976	1978	2006
COMFORTABLE	Staying indoors	-	$U_{mean} > 3.3$	$U_{mean} > 3.5$	-	-	-
	Staying outdoors in a stationary state	-	$U_{mean} > 5.4$	$U_{mean} > 5.3$	$U_s > 6$	$U_{peak} > 10$	$2.5(A)$
	Moving/walking	-	$U_{mean} > 7.9$	$U_{mean} > 7.6$	$U_s > 9$	$U_{peak} > 13$	$2.5 - 5$ (B)
Uncomfortable conditions		$U_{mean} > 13.8$	$U_{mean} > 5$	$U_{mean} > 9.8$	$U_s > 9$	$U_{U_{peak}} > 16$	5-10 (C)
Dangerous conditions		-		$U_{mean} > 15.2$		$U_{U_{peak}} > 23$	$10 - 20$ $(D) > 20$ (E)
Determination of peak and average wind speeds		$U_{peak} = U_{mean} + 2.68U_{rms}$	-	-	$U_s = U_{mean} + 3U_{rms}$	$U_{peak} = U_{mean} + 3.5U_{rms}$	-

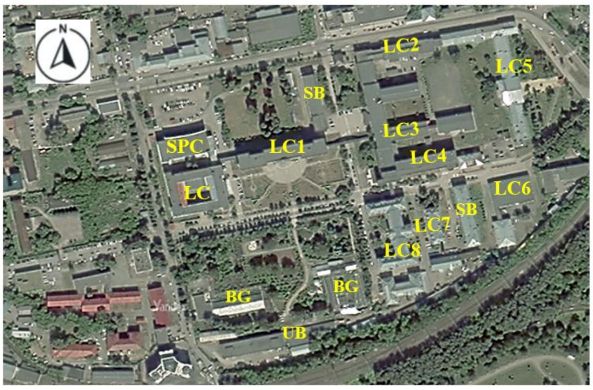
Note:
$\boldsymbol{U_{mean}}$ – mean wind speed, m/s;
$\boldsymbol{U_s}$ – equivalent-set velocity, m/s;
$\boldsymbol{U_{peak}}$ – peak wind speed, m/s;
$\boldsymbol{U_{rms}}$ –root mean square value (deviation), m/s.

The difficulty of applying one or another criterion lies in the fact that the wind regime of a given development is determined by the natural and climatic features of the territory in question, as well as the specifics of infrastructural development. Consequently, the aeration regime of one territory may differ significantly from that of another. In such a case, comfort criteria can be attributed to areas with similar natural and climatic features.

The development of numerical models and criteria in this area make it possible to determine what wind comfort conditions are formed in modern built-up areas. For example, in the work of Purvi P. Pancholya et al., a number of numerical studies were conducted to assess the influence of urban canyon geometry on pedestrian comfort, and the results obtained were used to expand the Beaufort scale [38-39] assessed wind comfort in high-rise buildings, which was determined according to the Beaufort scale and the NEN 8100 standard. Of particular interest are works studying the influence of high-rise buildings of complex design on changes in wind conditions, and assessing their influence on reducing the level of wind comfort in the pedestrian zone. With height, the wind speed increases, which leads to increased wind loads on the structural elements of buildings; these studies are presented in the works of Blocken et al. [27], Valger et al. [40], Wei Xu [19]. The formation of local acceleration zones as a result of flowing around the sides of buildings creates areas of separated flows with critically high speeds from the point of view of wind comfort [41-42].

Description of study area

As mentioned above, the campus of Perm State University (PSU) was selected as the study area. The campus encompasses educational buildings, scientific laboratories, student dormitories, university sports centers, and the life-supporting infrastructure (Fig. 1). The territory under consideration extends for 800 meters.



LC – Faculty of Chemical;
LC1 – Faculty of Geography;
LC2 – Faculty of Economics;
LC3 – University Administration;
LC4 – Natural Science Institute;
LC5 – Faculty of Modern Foreign Languages and Literatures;
LC6 – Faculty of Law;
LC7 – Faculty of Pedagogical;
LC8 – Faculty of History and Political Science;
SPC – Student Palace of Culture;
SB – Social Behavior;
BG – Garden named after A. G. Henkel;
UB – Utility Building.

Figure 1. The campus of Perm State University (PSU) as a study object.

A morphological assessment of the university campus was conducted, and the principal urban planning parameters that define the urban development were identified.

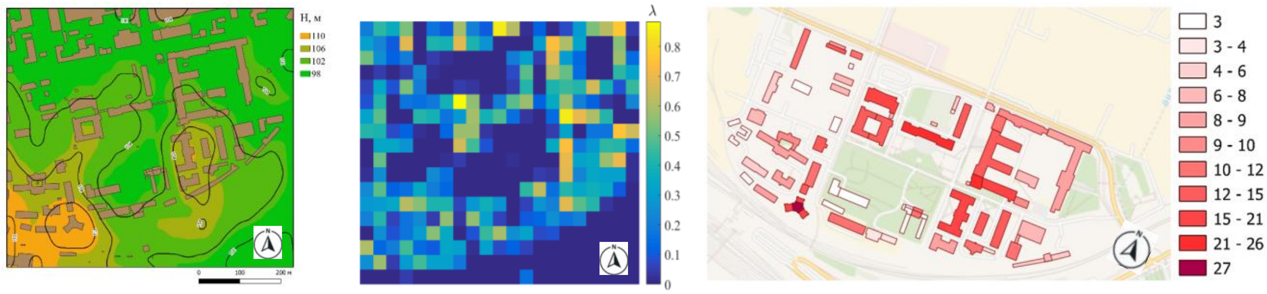
Terrain relief plays a significant role in the formation of urban landscapes and their subsequent development. Data from the Mapzen open-source mapping platform were utilized to describe the topography of the terrain. Upon examination of the university campus, it can be observed that there is a slight height difference of approximately 16 m throughout the territory. On the southern side, the territory is bounded by a railroad embankment with a height of 5 to 10 m. The majority of the territory exhibits a gentle level topography (Fig. 2a).

One of the principal indicators utilized in urban planning is the development density factor (λ) [43]. This factor determines the roughness of the underlying ground surface and, consequently, the wind regime. The optimal value for the development density factor for buildings of scientific purpose and specialized facilities is 0.6–0.8 [17]. The design development density factor reaches 0.8, which is an acceptable value in accordance with urban planning regulations (Fig. 2b).

The behavior of wind flows in the development and localization of different wind zones in the area where people reside is determined by the mutual location of buildings in relation to each other, their geometric shape, and height/number of storeys. Evaluating the buildings from the perspective of their geometric shape, it can be noted that the buildings of the line-pattern development prevail. Only the education building LC, which has a closed contour, stands out. It is noteworthy that the LC–LC1 and LC1–LC3 education buildings are connected by pedestrian crossover bridges situated at a height of 3 m from the ground (Fig. 1).

The assessment of building heights revealed that the university campus is comprised of structures of varying heights. The tallest building is approximately 27 m high, with buildings ranging from 15 to 21 m in height being the most prevalent (Fig. 2c).

The city blocks of the study area are occupied by vegetation of different heights. In the northern part of the block there is a group of tall deciduous trees (25 m), the crowns of some trees are converging (indicated by number 1 in black in the Fig. 4). In the southern part there is a botanical garden with trees of different species up to 15 m high (indicated by number 2 in black in the Fig. 4). In the campus, alleys of low deciduous and coniferous trees 6 m high are planted along the roads and border shrubs up to 1 m high along the paths. In some places you can find individual trees up to 20 m high.



a) b) c)

Figure 2. Morphological assessment of the Perm State National Research University campus: a) land topograph, b) development density, c) tallness of buildings.

2. Materials and methods

Data source

One of the objectives of the present study was to simulate specific wind conditions and to compare the results of numerical simulations with field observations at monitoring points in order to verify the numerical algorithms implemented in the SigmaEco specialized software module.

To assess the prevailing wind conditions on the campus and to gather the requisite data for subsequent numerical analysis, field observations were conducted. The research was conducted on June 13, 2023. According to observations from the Perm meteorological station (WMO index 28224), which is located 9 km from the research site, the weather was clear (Fig. 3). The air temperature had a daily variation from 2.4 °C in the morning to 22.7 °C in the afternoon.The relative humidity exhibited a correlation with the diurnal temperature variations, with a value of 89% observed in the morning and 31% at 5 p.m. local time. At the ground surface (at a height of 10 m), the wind speed exhibited a diurnal variation in magnitude and direction. During the night hours, a weak wind from the south-east and south was observed, with an average speed of 1 m/s. Following the sunrise and the warming of the suburban area, the wind speed increased to 3 m/s and began to change direction to the west. As the urban area warmed in relation to the area in which the weather station was located, the wind speed shifted to the south-west. After sunset, the wind speed decreased to 1 m/s. Consequently, the urban breeze circulation was clearly evident on the day in question due to the formation of the nighttime heat island. The Perm meteorological station is situated to the southwest of the city center. In the event of a heat island forming in stable temperature stratification, south and southwestern flows are observed.

Figure 3. Map-scheme of the location of the research object and the meteorological station Perm.

The MAWS201 and Davis Vantage Pro mobile weather stations were utilized as the primary equipment for this study. The elevation of the sensor measuring wind speed on the MAWS201 weather stations was 3 m, while on the Davis Vantage Pro weather stations it was 2 m. More detailed information about the measuring instruments is given in Table 2.

Table 2. Data Specifications

Measurement devices		Averaging time, min	Nominal accuracy (+/-)
Davis Vantage Pro	Wind speed	5	greater of 1m/s or 5%
	Wind direction	5	7°
MAWS201	Wind speed	10	0.3 m/s (< 10 m/s), < 2 % (> 10 m/s)
	Wind direction	10	3°

The initial monitoring point was situated on the roof of the LC1 education building, where the anemometer recorded wind speed at a height of 30 m above the ground. The second control point was situated in the rear of the LC1 education building, where data were recorded using the Davis Vantage Pro weather station. The MAWS201 weather stations were situated at control points 3 and 4. Control point 3 was situated on the northwest side of the campus, in close proximity to the Student Palace of Culture (SPC) in a parking lot. At point 4, the weather station was installed on the roof of a utility building at a height of 3 m. At control points 5 and 6, Davis Vantage Pro mobile stations were placed. Monitoring point 5 was situated in the eastern portion of the CL1 education building in close proximity to the pedestrian crossover bridge that connects the LC1 and LC3 education buildings. The control point 6 was situated in the public garden, which is situated in front of the CL1 education building (Fig. 4).

Figure 4. Schematic map of the location of monitoring points and an example of equipment placement.

A series of meteorological data on wind speed and direction were obtained as a result of field observations. The prevailing wind direction at each monitoring point was determined based on these data (Fig. 5). The analysis indicates that wind directions at monitoring points 1, 3, and 4 aligned with the background value of wind, as recorded at the Perm-West meteorological station. At points 2 and 5, deviations were recorded. At point 5, the prevailing wind direction is northwest, while at point 2, wind direction was northwest, northeast, east, and east-southeast. This phenomenon can be attributed to a change in wind speed direction when flowing around the SPC building. The flow around the building results in changes in the structural behavior of the flow, which leads to the appearance of whirlwinds. This increases the gustiness and directional variability. At point 5, the wind flow was deflected away from the south wall of building LC1 and formed a northwest local airflow. At point 6, the wind direction shifted to the south-southwest, west-southwest, and west sectors.

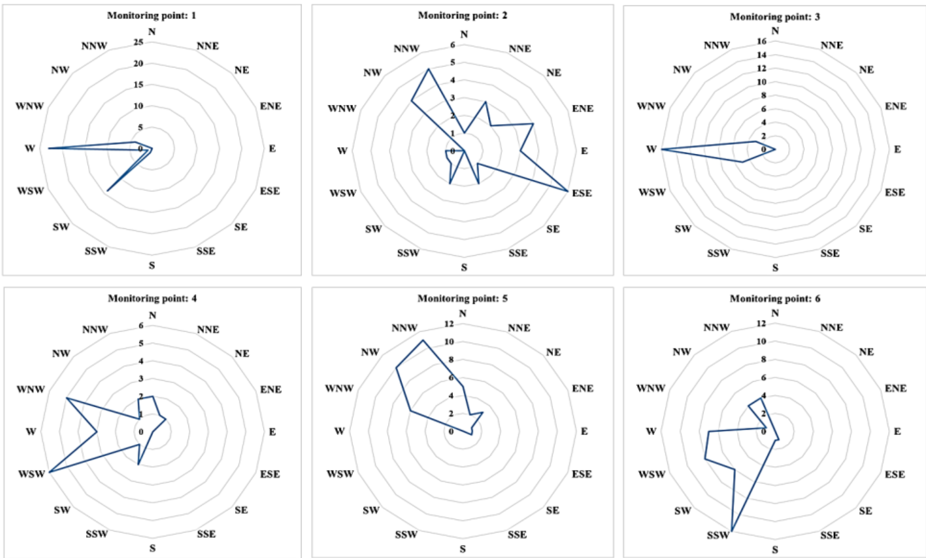


Figure 5. Wind regime diagram at monitoring points.

The data obtained at point 1 were subsequently adopted as boundary and initial conditions in numerical modeling. It is worth noting that at the first point there is a westerly wind, which is one of the prevailing winds, according to meteorological data from the Perm station (Figure 3). At point 1, time intervals were selected during which the wind direction remained virtually unchanged – 10:30-10:55 and 11:25-11:50 local time (UTC+5). A 50-minute interval was considered, within which 64 cases were realized. Average wind speed values were obtained at each monitoring point, which were determined as follows:

$$v_{ave_{Point_1}} = \frac{\sum_i v_i}{N} \qquad (1)$$

where $v_{ave_{Point_1}}$ is the avarage wind speed at point 1, m/s; is the number of observations during the measurement period; v_i is the wind speed of the i-th observation, m/s; N is the number of measurements during the observation period (Fig. 6).

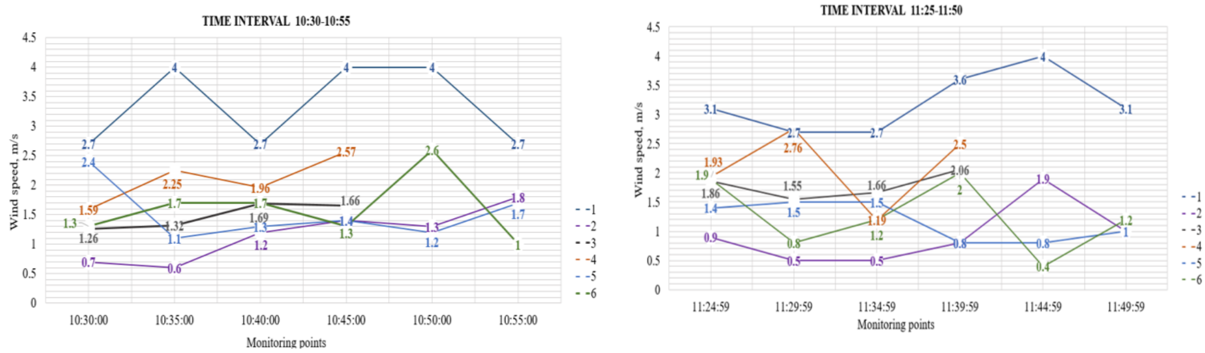


Figure 6. Graph of changes in speed values at monitoring points in the time intervals under consideration.

The obtained average wind speeds at the monitoring points during the considered time interval were taken further as control values (Table 3).

Table 3. Results of the analysis of field observations at monitoring points.

Number of the monitoring point	Time interval 10:30-10:55	Time interval 11:25-11:50
	Average wind speed, m/s	
1	3.35	3.2
2	1.2	1.0
3	1.5	1.7
4	2.0	2.0
5	1.5	1.0
6	1.6	1.3

Numerical model

To describe the wind flow, a microscale meteorological model developed to study the processes occurring in the city atmosphere is employed [44]. The model is based on the unsteady Reynolds-averaged Navier–Stokes (URANS) equations for incompressible flows[45].

The system of equations for averaged meteorological quantities includes:

– continuity equation:

$$\nabla(\rho_z V) = 0, \qquad (2)$$

– equation of motion:

$$\frac{d(\rho_z V)}{dt} = -\nabla p + \nabla[(\mu + \mu_t)(\nabla V + \nabla V^T)], \qquad (3)$$

where *d*/*dt* is the substantial derivative; **V** is the velocity vector, m/s; ρ_z is the hydrostatic density, kg/m^3; *p* is the averaged pressure Pa; μ is the dynamic viscosity, kg/(m·s); μ_t is the turbulent viscosity.

The distribution of hydrostatic air density ρ_z and pressure were calculated from a condition of constant distribution of potential temperature along the height.

The two-parameter URANS k-ω SST model [46] was employed to describe the turbulent characteristics.

The velocity distribution and turbulent characteristics were specified as inlet boundary conditions[47]:

$$u(z) = \frac{u_*}{K}\left(ln\left(\frac{z - z_0}{z_0}\right)\right),$$

$$\omega(z) = \frac{u_*}{K \cdot z \cdot \sqrt{C_\mu}},$$

$$k(z) = \frac{u_*^2}{\sqrt{C_\mu}},$$

where *K* = 0.41 is the Karman constant; u_* is the dynamic velocity of the atmospheric boundary layer; z_0 is the surface roughness, m; $C_\mu = 0.09$ is the constant. At the entrance and further on the ground surface, a roughness value of $z_0 = 0{,}05$ m.

To describe the velocity profile with roughness near the wall, wall functions are used based on the aerodynamic roughness model proposed in the work of P.J. Richards and R.P. Hoxey:

$$U^+ = \frac{1}{k}\ln\left(\frac{y^+ + z^+}{z^+}\right),$$

$$\frac{dU^+}{dy^+} = \frac{1}{K(y^+ + z^+)},$$

Dimensionless quantities are defined through the viscous scale $\delta_\nu = \frac{\nu}{u_*}$ as follows:

$$z^+ = \frac{z_0}{\delta_\nu}, y^+ = \frac{y}{\delta_\nu}, U^+ = \frac{\Delta U}{u_\tau}.$$

where ν – kinematic viscosity at the wall, m/s^2.

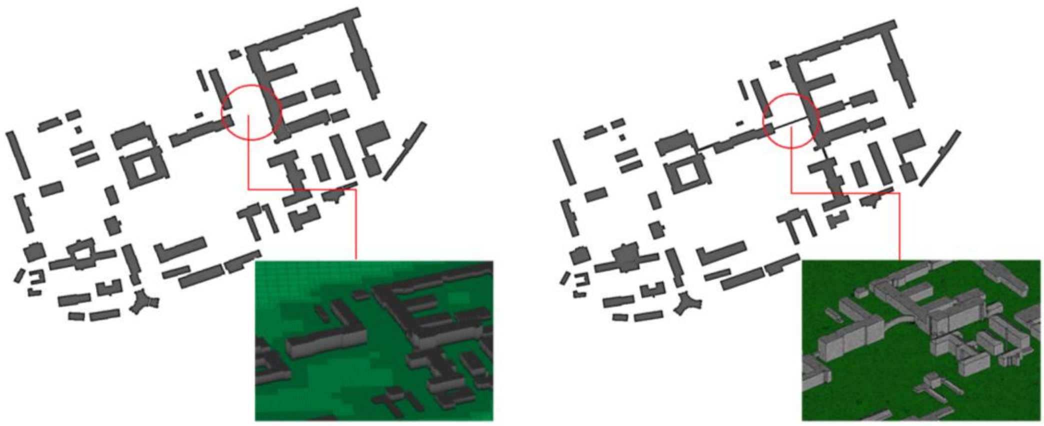
Setting of tasks

The objective of this study was to investigate the impact of geometric similarity between buildings, pedestrian crossover [48] bridges, and urban infrastructure on the quality of numerical simulation results. The findings of this study will assist in determining the requisite degree of 3D urban model refinement for the optimal prediction of wind conditions and the determination of pedestrian wind comfort conditions.

Two 3D models of the university campus with differing levels of detail applied to the objects under development were utilized.The results of the computational variants are presented in Fig. 7.

In the first variant, the buildings were represented in a simplified form, with roofs assumed to be flat and pedestrian crossover bridges not included. In this variant, an unstructured computational hexahedron mesh was constructed. The principal advantage of this mesh is that it does not necessitate the meticulous elaboration of the input data. The geometry and height of the buildings were sourced from OpenStreetMap. It is important to note that the boundaries of the buildings were delineated by blocking cells, which resulted in the formation of stepped surfaces at the boundaries (Fig. 7a).

In the second variant, the full geometric similarity of the buildings was considered, with roof shapes and pedestrian crossover bridges being reproduced (Figure 7b). In this variant, an unstructured computational polyhedral mesh was constructed. This mesh allows for the complete representation of the contour of buildings and constructions. However, the implementation of this mesh necessitates the development of detailed geometry using additional computer-aided design (CAD) programs, which entails additional labor costs.



a) b)

Figure 7. Geometry and computational meshes of the considered numerical computation variants: a – Variant_1, computational hexahedron mesh, b –Variant_2, computational polyhedral mesh.

The problem was solved on the basis of non-stationary equations (2-3) with stationary boundary conditions. The presented modeling results are an averaged steady flow. The time step was set to one second, which permitted the Courant–Friedrichs–Lewy mesh criterion (convective CFL) to be maintained in the building region at a value less than two (CFL ≤ 2).

In both variants, the mesh spacing in the horizontal plane near the buildings was set to 1 m. For each calculation, three calculation grids with different levels of detail were prepared (Table 4). The height of the calculation area is 250 m, the width is 700 m, and the length is 1100 m. To assess the pedestrian wind comfort level in the territory under consideration, the following boundary conditions were adopted (Table 4):

- the velocity profile at the inlet was set according to the logarithmic law $v_{h_{30}}$= 3.35 m/s (velocity at a height of 30 m);
- west wind direction was assumed.

Table 4. Setting up tasks.

Type of calculation grid		Number of calculation cells	Wind speed at the entrance, $v_{h_{30}}$, m/s	Wind direction, °
hexahedron	polyhedral			
Variant_1_coarse	Variant_2_coarse	≈ 4×10^6	3.35	270
Variant_1_base	Variant_2_base	≈ 8×10^6		
Variant_1_fine	Variant_2_fine	≈ 15×10^6		

3. Results and Discussion

A quantitative comparison of the numerical study results of the considered variants with field data at the control points revealed that the geometric detailing of the objects and the type of mesh significantly influence the obtained computation results (Figure 8). In the case of Variant_1, a satisfactory comparison is observed for control points 1, 2, 3, and 6, while significant discrepancies from the field data are observed at points 4 and 5. The implemented approaches in Variant_2 demonstrate a satisfactory match. The numerical values obtained fall within the range of wind speed variation during the period of field observations and are maximally close to the control values. A discrepancy is observed at point 4, which may be attributed to the fact that the 3D model of the object represented only buildings and structures, while the high vegetation in the vicinity of point 4 observed when considering the city landscape map may contribute to the wind flow behavior (Fig. 8).

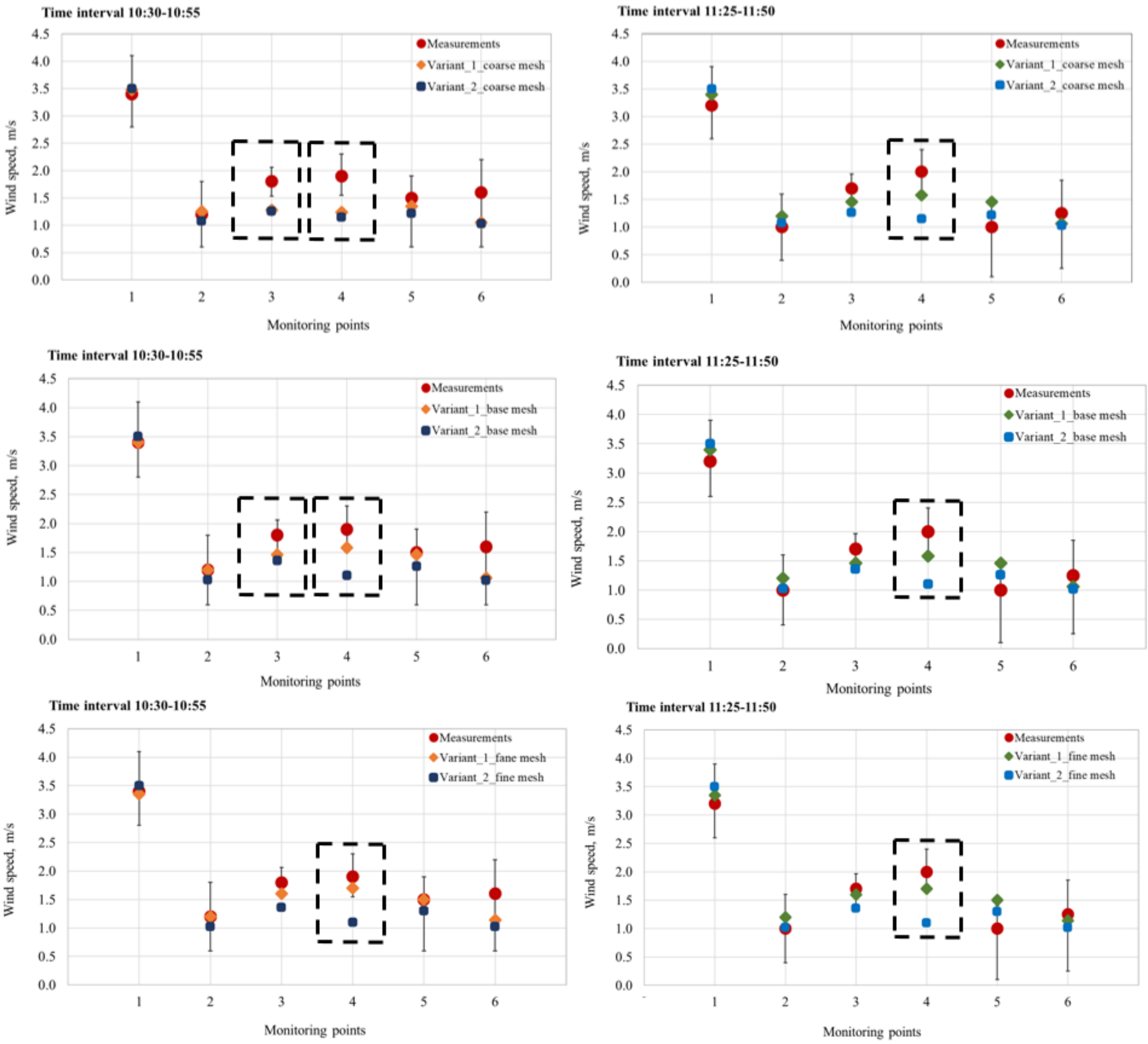


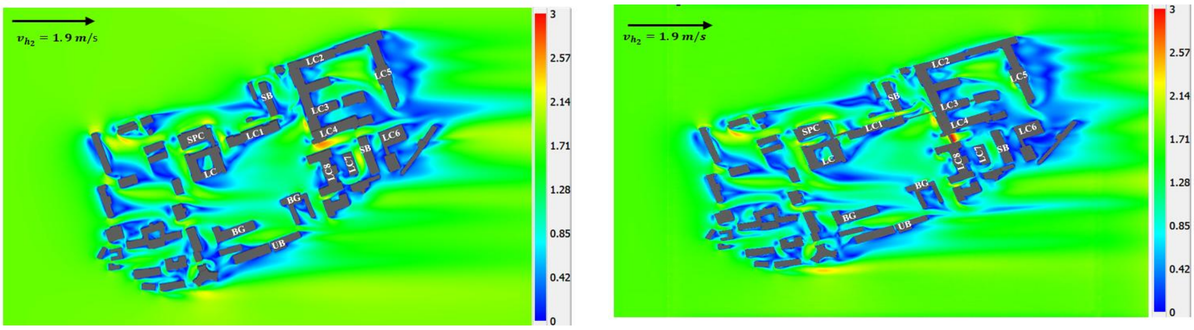
Figure 8. Comparison of the results of the numerical study with the data of natural observations in the considered time intervals.

It is worth noting that the numerical results obtained using computational grids of $\approx 8\times10^6$ and $\approx 15\times10^6$ demonstrate similar results, which indicates that the level of grid detail up to 8×10^6 is optimal.

Based on the data obtained, the average relative deviation of the results of the calculated study in relation to the data of natural studies in time intervals was calculated. For the time interval (10:30-10:55) they are equal to - 0.28, and for the second interval (11:25-11:50) - 0.26.

Below is an analysis of images for variants with a basic grid (base), since this detailing is sufficient for conducting this type of research. The grid (coarse) demonstrates not entirely satisfactory results, and the detailed grid (fine) is computationally expensive. The analysis of the aeration conditions was performed for the optimal calculation grid – basic $\approx 8\times10^6$.

From an analytical perspective, the results obtained at a height of 2 m above the ground surface are of particular interest, because the main human activities in the street space are observed in this elevation range. The results of the conducted study are presented in the form of a velocity field, as illustrated in Fig. 9.



a) b)

Figure 9. Velocity field in a horizontal cross-section at a height of 2 m: a – Variant_1_base, b – Variant_2_bas, (m/s).

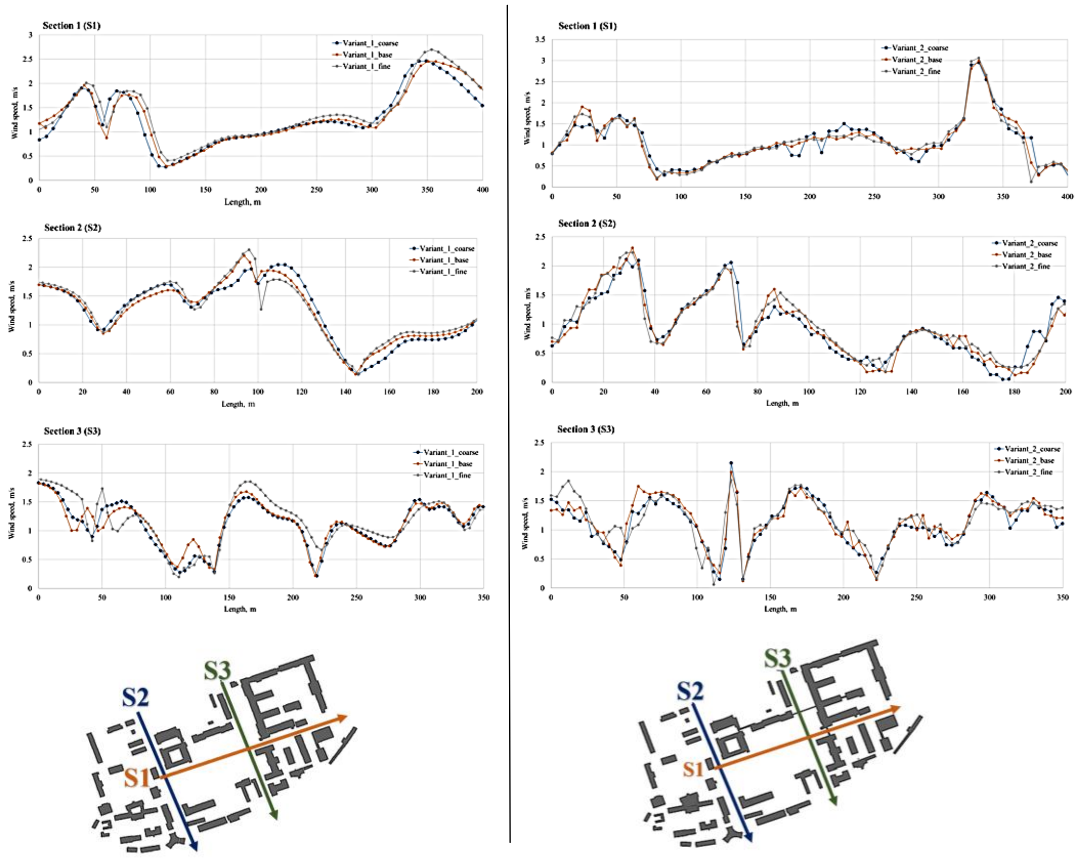
An analysis of the flow patterns depicted in Figure 9 reveals that at the inlet, the wind speed at a height of 2 m is approximately 1.9 m/s, while throughout the campus the wind speed varies between 0.1 and 3.2 m/s.

The configuration of the buildings and their positioning relative to one another result in the formation of areas with low air circulation. Courtyard spaces exhibit the formation of wind speed zones with underestimated speeds ranging from 0.1 to 1.0 m/s. From this, it can be inferred that the topology of the university campus development contributes to the formation of large-scale stagnation zones.

The main increase in wind speed is observed in places where the airflow streamlines the edges of buildings. Vortices are disrupted from the side edges of the buildings, forming detached flows which results in an increase in velocity of up to 3.0 m/s. Between buildings LC4 and LC8, the Venturi effect [xx] is observed, which is accompanied by an increase in velocity up to 3.2 m/s.

It is noteworthy that the overall wind pattern of the area in both computation variants exhibits a similar character (Fig. 9a, b). During the detailed analysis, it was revealed that despite the formation of the same wind zones, the velocity regimes within them differ. To illustrate this phenomenon, three cross-sections were selected in which the velocity distribution along the length of the selected section was considered.

Considering cross-sections 1 and 2, a quite similar wind profile is observed (Fig. 10, b). At the same time, in the case of Variant_1, the velocity profile is observed to have a smoother character, with a gradual change in velocity. In contrast, in the case of Variant_2, the velocity profile is observed to have a jump-like appearance, characterized by the appearance of peak velocity signs, particularly in the local acceleration zones. The velocity profile in cross-section 3 (S3) allows for a clear demonstration of the impact of the pedestrian crossover bridge on the wind speed regime. An analysis of the velocity profile (Fig. 10) has revealed that in the absence of the pedestrian crossover bridge in the computations, the velocity in this section varied between 0.1 and 0.7 m/s (Variant_1). In contrast, the presence of the pedestrian crossover bridge (Variant_2) resulted in a doubling of the velocity regime, with wind speeds varying between 0.2 and 1.8 m/s.

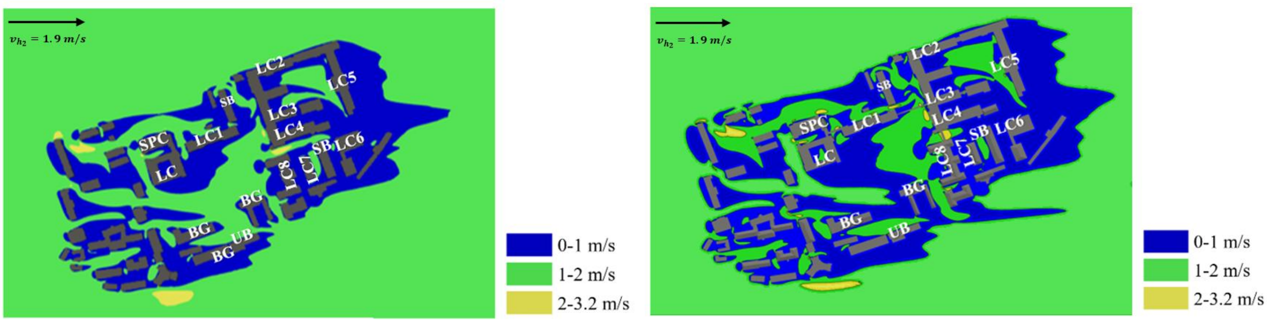


a) b)

Figure 10. Wind speed profile in the considered cross-sections: a) Variant_1, b) Variant_2, m/s.

It should be noted that for Perm the prevailing winds are Southern, South-Western and Western winds. The average long-term wind speed for June winds is about 3 m/s. The conditions under consideration in the work are typical for the city in the summer period, in this regard, the wind comfort criteria NEN8100 were used to assess the wind comfort conditions.

A functional zoning analysis of the campus based on pedestrian wind comfort levels has revealed that, at the considered boundary parameters, favorable human habitation conditions prevail. The wind speeds do not exceed 5 m/s and correspond to the A and B classes of environmental comfort (Fig. 11).



a) b)

Figure 11. Schematic map of the wind zones location according to the wind speed regime: a – Variant_1_base, b – Variant_2_base.

5. Conclusions

The results of numerical and experimental studies of wind pattern conditions in the territory of the Perm State University (PSU) campus have yielded the following important scientific results that are applicable in practice:

– The SigmaEco mathematical microscale meteorological model, implemented in the SigmaFlow software module and based on the meteorological parameters, obtained in the course of field studies, was verified.

The outcomes of the study have demonstrated that the employed numerical algorithms are capable of accurately simulating the physical processes associated with wind flow mechanics. The average relative deviation of the results of the calculated study in relation to the field study data over the entire 50-minute time interval is 0.27.

– The influence of geometric similarity of buildings, pedestrian crossover bridges, and urban infrastructure, as well as the type of computational mesh on the quality of numerical simulation results was elucidated.

Two distinct computational variants were developed. In the first variant, buildings were represented in a simplified form, with roofs assumed to be flat and pedestrian crossover bridges not reproduced. An unstructured computational hexahedral mesh was constructed. In the second variant, the full geometric similarity of buildings was considered, and roofs and pedestrian crossover bridges were reproduced. An unstructured computational polyhedral mesh was constructed. The results obtained have revealed that the geometric detailing of the study objects is necessary for qualitative prediction of the wind aeration regime conditions of the territory, and, consequently, for determination of the pedestrian wind comfort conditions. The obtained quantitative results in the second option demonstrate a better agreement with field data. It should also be noted that the presence of pedestrian crossover bridges in the building development leads to the emergence of areas with zones of local wind acceleration, which cannot be ignored, since the wind speed in these zones increases twice.

For each calculation, three computational grids with different levels of detail were prepared: coarse $\approx 4\times10^6$, basic $\approx 8\times10^6$, fine $\approx 15\times10^6$. The basic grid (basic) is optimal, since such detail is sufficient for conducting this type of research. The grid (coarse) shows not entirely satisfactory results, and the detailed grid (fine) is computationally expensive.

It should be noted that the external climatic conditions in urban development are largely determined by the temperature regime of the territory. Building materials of structures, roadbeds, etc. lead to changes in the natural heat balance of the ground surface by increasing the temperature in the built-up urban neighborhoods compared to the territory adjacent to the city. Based on this fact, megacities act as accumulators of a larger portion of incident solar energy. The presence of additional sources of anthropogenic heat also aggravates the situation. Reduction of vegetation in urban areas results in a decrease in the average rate of evaporation from the ground surface, which also affects the temperature regime of the territory. Collectively, these factors contribute to the formation of urban heat islands (UHI). Also, the research has revealed that failure to take into account vegetation in the numerical study leads to the appearance of incorrectness in simulation. Consequently, microscale mathematical models for urban environments must take into account the aerodynamics and heat and mass transfer processes.

Collectively these conditions have a very strong influence on the temperature and humidity perception of the urban environment by humans, and therefore, the assessment will necessitate the integration into the microscale model of complex comfort criteria, which will allow assessing the environmental conditions, taking into account the wind, temperature, and humidity factors of the urban environment.

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