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ARTICLE

Urban Design Embracing the Wind Environment: Bezigrad Neighbourhood Case Study in Ljubljana, Slovenia

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ARTICLE INFO

Article history
Received: 5 March 2020
Accepted: 12 March 2020
Published Online: 30 April 2020

Keywords:
Urban climate
Wind theory
Typology of buildings
Morphology
Landscape

ABSTRACT

Urban climate is considered one of the most important environmental criteria in urban planning, since it significantly affects the project and its placement in the space. Climate conditions are central to the study, with winds in the urban environment, their direction, intensity and changes taken into consideration designing the new interventions in space. The results of the case study were applied to the project with the intention of supporting and guiding the urban design in order to improve the comfort and quality of the environment. In this article, I explore the question of how individual morphological models affect the micro- and macroclimate conditions. The initial urban solution of the Novi Bezigrad neighbourhood is presented as a realistic model project responding to the existing urban and architectural practices and legal provisions. The project was tested in a computer model and was analysed in terms of the positive and negative effects of its impact on the wind in the planning area and the wider area in the surrounding area. The final urban design derives from the results of wind analysis.

1. Introduction

The central topic of the study are microclimatic conditions, which are multifaceted and intertwined, as they interact with meteorological conditions of the city. The importance of microclimatic conditions, especially winds in urban design, has been recognized for millennia. There is ample evidence that the prevailing winds have placed a great emphasis on settlement planning by ancient civilizations [1]. In the city of Kahun in 2000 BC, the Egyptians organized the apartments in such a way that the western part, where senior officials were housed, was protected from the hot Saharan winds, while at the same time being able to take advantage of the cooler winds from the north. In the 1st century BC, the Roman architect Vitruvius in his works described a detailed plan of how the Roman outposts were perpendicularly superimposed to the orthogonal street grid, in order to block strong winds and mitigate the cold weather in front of gardens, entrances and yards. At the end of the 19th century, the knowledge of the prevailing winds was first used the planning of Vienna, to protect residential areas from factory chimney discharges [1]. Pogačnik [2] points to the wind as an important influencing factor in settlement planning.

Air currents have both negative and positive characteristics and are desirable in certain situations. They can be pleasant for the pedestrian if they are weak, brief or uncommon and if they bring in the fresh air. On the contrary, they can be bothersome when they are constant, powerful, and if they bring in pollutants. On the outskirts of cities and in ru-

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 DOI: https://doi.org/10.30564/re.v2i2.1739

ral areas, they are generally less desirable than in urban areas [2]. Wind speed is an important parameter in urban areas, as it affects the health, the comfort of the outdoors by reducing the sensation temperatures and even the atmospheric temperatures themselves. Adapting the urban structure can have a significant effect on experiencing the urban heat island in urban environments with adequate ventilation and openness to the winds. The cooling effect, where the wind goes over human skin is estimated at 3.6 °C for every 1 m/s with which wind speed is increasing. This means that the wind speed of 2 m/s can already have a significant cooling effect at 7.2 °C [3]. In the study of connections between the intensity of the urban heat island and wind speed, analyzed the surrounding areas of Melbourne, Australia. Their main findings showed that calm winds and a clean atmosphere lead to increased urban intensity of heat fluxes. It was found that, in the summer months, the speed increase of 1 m/s causes a decrease in heat intensity measured at 0.14 °C [4]. The cooling the effect of wind in this way helps to mitigate the adverse effects of heat island to the microclimatic conditions and comfort of space users. In tropical regions such as Singapore, the observed cooling effect was the same as a temperature drop by 2 °C [5].

When an effective urban solution is desired, it is appropriate to use simulation techniques or to use those methods that have already been proven and meet the expected goals. The aim is to provide better insight into the living condition of pedestrians and residents and in general all users of the neighbourhood in question. Such analytical approaches are present in urban and architectural design, but they do not include all the influential factors of space. Such an approach would, in principle, be costly, time-consuming and in most cases likely to be limited in its own right. In my research, I focus on the aerodynamic properties of the urban environment: the direction, the intensity and their dependence on physical structures, in the light of new urban interventions. Individual changes in space are evaluated separately and combined in a single model. In the selected case, I wanted to achieve an improved urban solution by taking into account the feedback loop of the wind simulation method.

The question is raised as to how the individual morphological models or different construction techniques affect the micro and macro conditions of urban climate in space. The case study contains a complex urban solution for a neighbourhood with a mixed-use design consisting of specific activities and building typologies that reflect the wider boundary conditions of the settlement. The solution is a model of a realistic project, presented as a reflection of the existing urban and architectural practices and legal provisions, taking into account good living conditions and urban context.

2. Methods and Materials

The urban project is presented in a computer model and analysed in terms of the positive and negative effects of its impact on the wind in the planning area and on the wider surrounding area. The final plan is derived from the results of the wind analysis. The working hypothesis of the assignment is that those simulation models of building types will exhibit diverse behaviour and will exhibit unique ventilation capacity in a virtual wind tunnel. With the results of the favourable typologies, I selected those buildings with more desirable results, thus adapting the project of the neighbourhood, so that the arrangement will be more acceptable for placement in a wind-vulnerable space concerning the wind corridors. Furthermore, it should display a better ability to transfer air masses.

Phase 1: Selection of morphological units for the treatment area in Ljubljana.

Phase 2: Individual unit evaluation.

Phase 3: Design and testing of the three project models.

Phase 4: Assessment of the results.

Phase 5: Depiction of the selected units on the project.

Phase 6: Reflection on the new design and the simulation methods used.

Any ground level objects, whether they are buildings or vegetation, are, to some extent, inhibiting wind speed. The slower moving layers affect the faster moving layer and vice-versa. In this way, the displacement energy is transmitted downwards and transferred to the solid surface by the ground friction. The winds are therefore stronger in altitudes, with the ground speed decreasing and changing in direction, as it gets closer to the surface. Because of this, we say that the wind has a vertical profile. The air pressure or air density decreases with height almost entirely exponentially, which is also related to the temperature, which as a rule increases with altitude [6]. In general, wind conditions in the urban area allow for ventilation of buildings and outdoor surfaces, affect the exposure of pedestrians outside buildings, alter the intensity of heat island occurrence and affect the ventilation of polluted air. Therefore, the ability to record wind flow and the ability to adapt to wind conditions in spatial planning is one of the major responsibilities of architects and urban planners [7].

In the urban area, wind speeds can change three to five times over a distance of a few meters. Considering the effect of turbulent wind on pedestrians, Arens [8] examines the mechanical effects of wind, from disturbance of clothing and hair to walking resistance and loss of balance. The author found that the effect of turbulence depends on the specific circumstances and activities of the the pedestrians. The turbulence intensity in areas of strong channelled

DOI: https://doi.org/10.30564/re.v2i2.1739

flows was measured as relatively low [8].

A study of urban aerodynamics, which also included an analysis of urban vegetation, found that wind speed and tree canopy resistance were closely related to the density of the urban area [9]. Strong correlation also exists with the typology of landscape arrangement and species of tree canopies, but for all species, the study found that the coefficient of air resistance varies with urban density. As the resistance of buildings is greater than the resistance of vegetation in the densely populated urban areas. The high density of the urban area causes a weaker wind environment and planting more trees does not slow down the already reduced wind speed. In a study involving CFD simulation, different resistivity values for individual tree species were included in the study [9].

3. Results: Well-being in Open Spaces

The initial objective is to test the existing urban models in a simulation. This is partly in service to the software testing, making sure the computer simulations in a wind tunnel are reliable. The results are supposed to show the results, which will be comparable to the established studies of wind, analyses of morphological models. The results of the preliminary set of morphological typologies and their analyses are applied to the project site, where individual units with favourable results are used in the urban development plan. In the simulations, I address only those typologies of housing that are relevant to the neighbourhood project.

3.1 Density Fields and Distances between Objects

The first part of the test covers the analysis of the offset between objects in a single size denominator of the objects. I simulated wind flow at three different building densities, where the land cover factor (LC) is at 10, 20 and 40%, depending on the distance between objects. This is 1*e*, 2*e*, and 3*e* of the height of object e. In my own case, at larger distances, I notice a larger isolated vortex, while at higher densities, winds slip through the model. The 1:2 and 3:5 ratios thus allow for greater weathering at lower density (Figure 1-2). The wind speed and polygon sizes are standard.

Different flow regimes across building blocks were identified on the selected models. With a smaller deviation between buildings (1:3), there is a clear overflow over the canyon (the space between buildings) and the stationary air within. With a larger offset, there is an interruption of downstream flows toward the canyon floor and swirls on both rear sides of the buildings. Separate turbulence within the canyon does not occur at the ratio of 3:5. Such regimes have been validated by numerous case studies [10]. When the area of the inner atrium (the space of a street canyon) is warm, at low wind speeds, thermal convection occurs, which shears on the direction of normal wind currents. Stable vortices in the canyon either prevent this or improve the intensity of the turbulence and reduce the warming effect [11]. Here, the flow patterns depend on the height of the adjacent building (h1) and the height of the opposite building (h2), as well as the distance between them.

Figure 1-2. Variable density at different configurations of unit spacing and the angle of unit separation (45, 27, 18) (left) and the predicted vortex display and their ventilation potential (right)

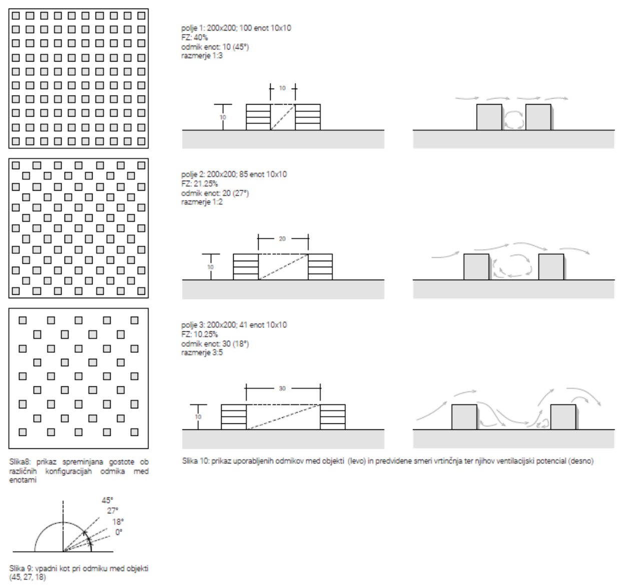


Figure 1-2. Unit separation distances (left) and the predicted vortex directions and their ventilation potential (right)

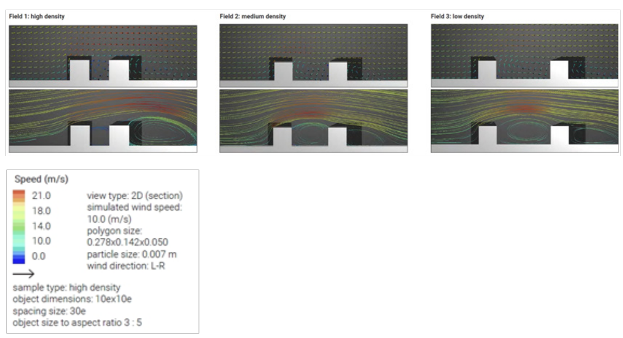


Figure 3-5. Vortex display with vectors (top) and bars (bottom). Field 1 – 3

3.2 Terraced Division of Buildings

The second part of the test involves assessing the different typologies of objects, based on the (illumination) angle of their terrace floors. In sample no. 1, the simulations are performed on four typologies with angles of 60 °, 45 °, 30 °,

 DOI: https://doi.org/10.30564/re.v2i2.1739

and 15 ° (Figure 6). From the representation of the vortex direction by vectors (Figure 7), we can see at which places the backward turbulent flows occur, in the opposite direction of the simulated flow. Most turbulence and velocity occur in type III. Compared to the building typologies of undivided structures, terrace types bring greater weathering to the rear of the building and greater turbulence.

In sample no. 2, I evaluate the relationship between the field density and the distance between objects in the typology of a divided object with a terrace accounted for a symmetrical and asymmetric layout. The design of the building illustrates the typology of the building, which is often seen in residential buildings - a building with floor of up to five, with a terrace. The unit offset is again illustrated in 1:3, 1:2 and 3:5 ratios. I found the results of the asymmetric layout satisfactory (Fig. 9), yielding a significant effect on turbulence. On the selected models, I study smaller-scale models in such a way that they simulate the expected results in the mathematical calculations of wind motion in meteorological surveys of urban environments. The time interval, which is important and significant in terms of the daily and seasonal variations, is omitted in the simulations in order to assess the maximum effects of the dimensioned shapes and their deviation from the average values of the selected model.

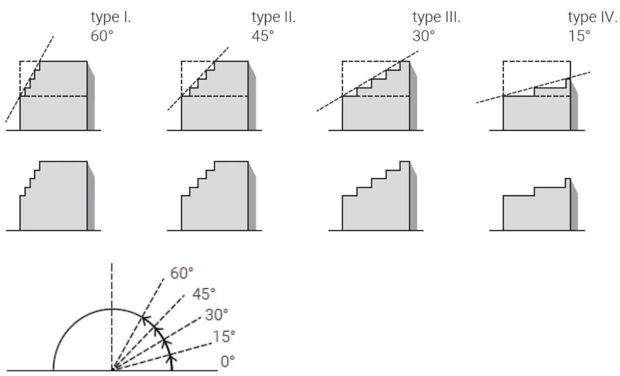
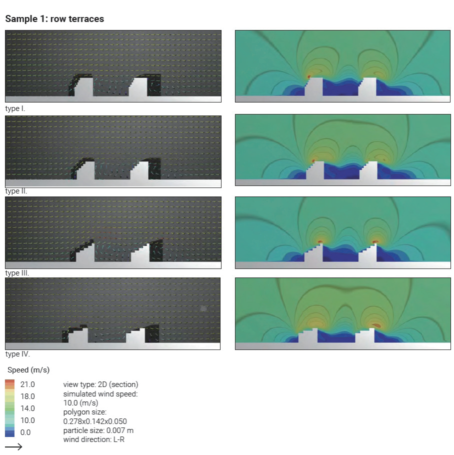


Figure 6. Terrace size - buildings at different slopes



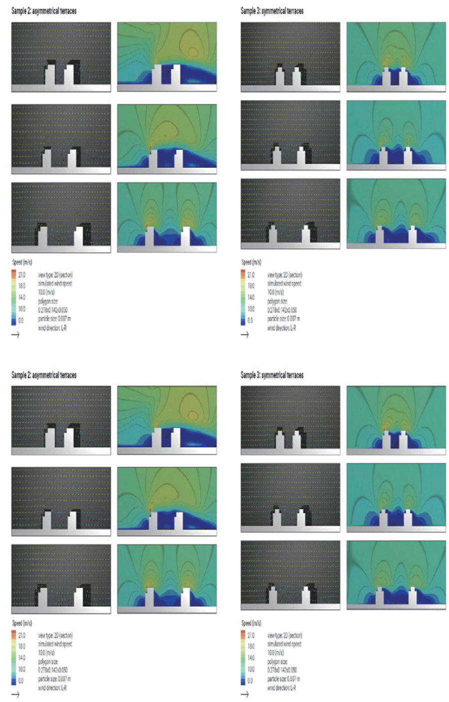


Figure 7-9. Asymmetrical and symmetrical terraces configuration effect on turbulence

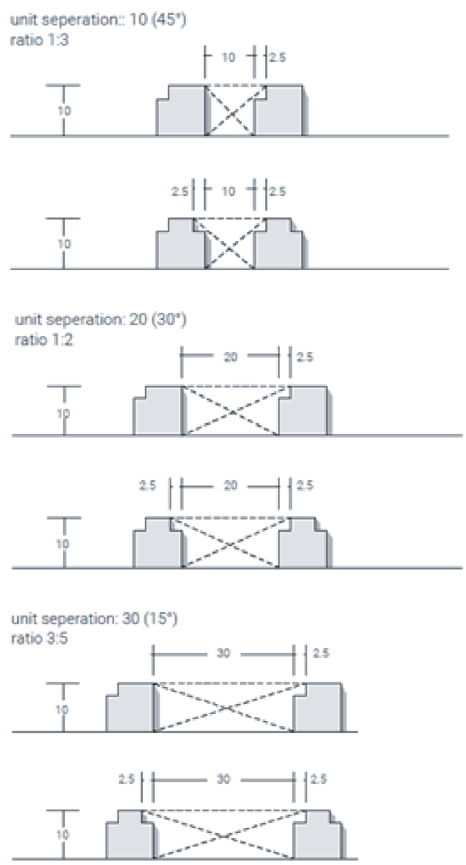


Figure 10. Asymmetrical and symmetrical terraces and their offsets

DOI: https://doi.org/10.30564/re.v2i2.1739

3.3 Evaluation of the Building Blocks

Due to the height of the construction and the introverted nature of the building-block configuration, I assume that these facilities offer worse weather conditions. However, it does offer other positive features, such as a rational density, equivalent living conditions and a comfortable street profile for pedestrians. The last part of the simulations covers the building blocks with peripheral street mass and the effect of their breakthroughs on the wind currents within them.

Through opening of the building block, it responds to the need of public space, connecting the public and private space, improving the transitivity, achieving the connection of the green system, providing better illumination and it influences the hierarchy of the volume relations between the built and open space. The circumference is open on one or both sides in the opposite or adjacent directions. It is divided into post-individual lamellae or blocks with its own entrances and vertical cores. In the process of selecting typologies, I considered the typical ways of dividing a building island by opening the perimeter. First on one side and then on the other, and by multiplying the openings. The following samples 1-8 are:

(1) Partially-closed block - type U in 0 ° offset,

(2) open block -type U in 0 ° offset,

(3) open block -type L in 0 ° offset,

(4) open block -type L in 0 ° offset,

(5) closed block -type L in 0 ° offset,

(6) open block -type T in 0 ° offset,

(7) open block -type T in 90 ° offset,

(8) open block -type O in 0 ° offset,

(9) open block -type O in 90 ° offset.

The offset indicates the alignment of the opening with the direction of the air currents. Typologies (U, L, T, O) of equilateral building blocks indicate different ratios between openings and their sides (a: b) (Figure 11). Each of them has the same ratios of 1:10, 1:5, and 1:3. I found that there is no significant difference in the particle simulation wind speed, so it remains standard for all samples at 10.0 m / s. The same applies to the size of the polygon (1.0 x 1.0 x 0.99) and the particle size (0.003 m).

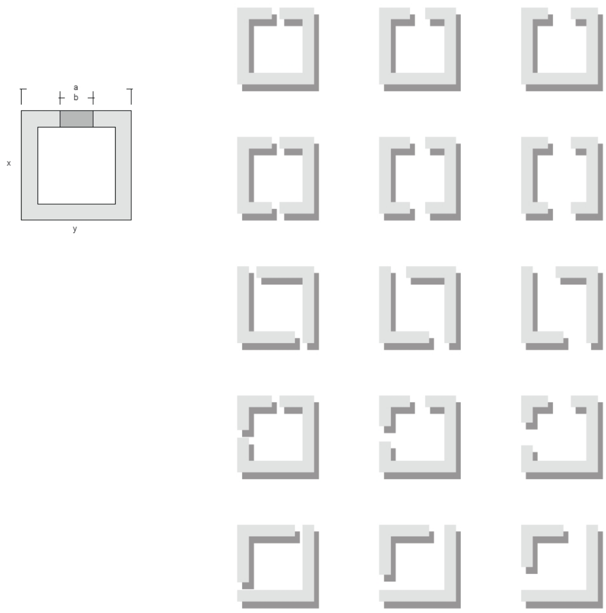


Figure 11. Demonstration of different buildings typologies within a block (x: y = 1: 1) presented with the ratio of the aperture on the edge (a: b)

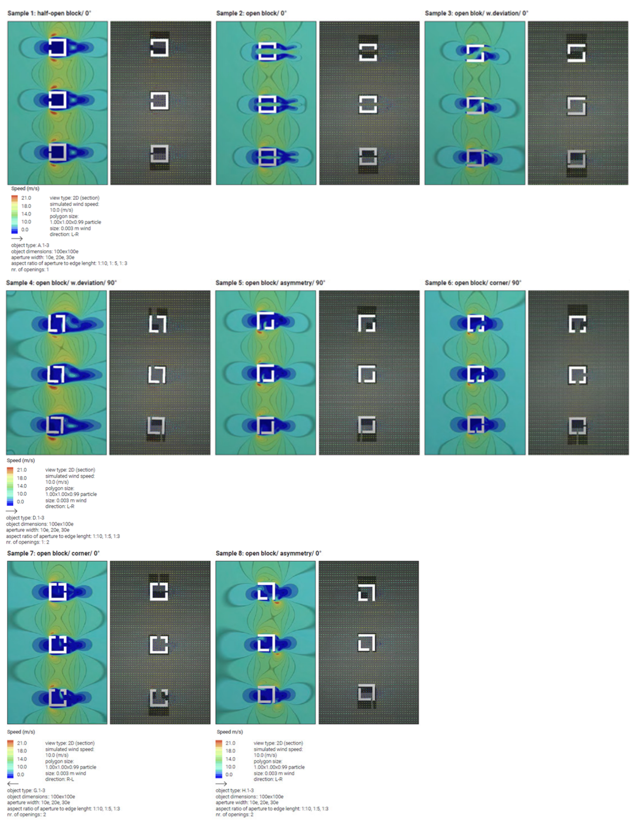


Figure 12-14. Wind power in bands (left) and vortex direction with vectors (right) on building blocks

In the building blocks with four to five floors or more, the open spaces are necessary. At the low-floor typologies with a ground floor or two-floor construction, or with a relatively

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large internal atriums, the typology itself allows a tunnel of air to be drawn inward [9]. From the results, I find that breakthroughs only work effectively in some samples. There may also be an increase in speed at the entry of wind through the vent due to the Venturi effect. For the needs of the project in the examples presented (Figures 12-14) I conclude that a ratio of 1:10 does not produce satisfactory results. The typologies where units have an indirect breakthrough at 90 ° show a suitable outcome at a 1:3 ratio. Hence, the way articulated geometry allows for a greater degree of ventilation.

4. Case Study: Bezigrad Neighbourhood, Ljubljana

The general direction and the wind power inputs are standard on all tests, as well as the particle sizes and the test polygon. The input data accurately reflects the actual weather conditions measured at the Ljubljana Bežigrad Meteorological Station, taken within a period of 2017-2018. Fig. 15 shows a scheme of the general directions of the morphological structure of the area and its road network and a scheme of the wind directions and gusts from the northeast (NE) and southwest (SW) winds. The cross sections *p1* and *p2* are placed taking into account the new development and wind directions.

The initial urban and architectural construction reflects the expected project development of the area, taking into account all program requirements, urban parameters and municipal regulations from the municipal spatial plan. The articulation is defined with the project areas with the required density, using closed quarters, which allow adequate sunlight, the use of space, views and satisfy other essential urban design elements based on the program requirements of the area. The design is built on an existing building network that was fabricated based on structural analysis. One of the requirements of the simulations performed is to determine how the given structure responds to the environmental conditions of winds and how it can be further improved. The following section presents wind tests and simulations conditions, first at an existing location (Figure 16-17) and then at final project variant (Figure 18-22) (out of three) where each is modified according to the feedback of previous results, where changes and adjustments have been taken into account.

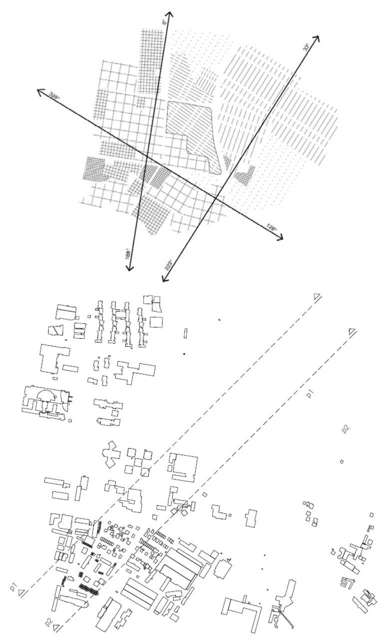

Figure 15. General directions of the morphological structure of the area and its road network (left) and the directions of the wind gusts from the northeast (NE) and southwest (SW) winds (right)

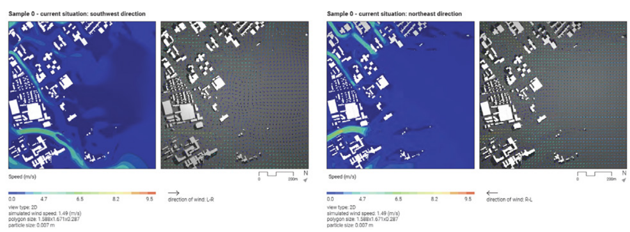

Figure 16. Wind power in bands (left) and vortex direction with vectors (right)

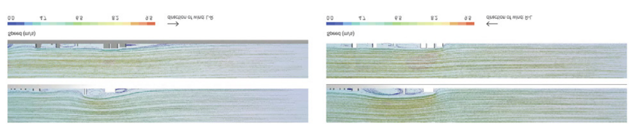

Figure 17. Directions of airflows with cross section vectors - Example 0 - SW direction (left) NE direction (right), cross section

The use of Wind Models in the Neighbourhood Evaluation

In Model 1 (Fig. 18-22), on the vector representation of the northwest wind flows, we can determine many “dead” zones of stagnant air. Closed quarters performed worst in the case of point *b*.

The building blocks of the northern part of the area in case of point *a*, also exhibit poor ventilation, which

DOI: https://doi.org/10.30564/re.v2i2.1739

are open only on the south side. In the eastern part of the model, the lamellae of the row houses are positioned unfavourably to the wind direction, as is a similar case in the south corner. The *e* point shows a strong barrier to the north face, where relatively strong winds are present, relative to the rest of the area. Comparable effect applies in the southwest wind direction. Special mention should be given to the western side NE wind exposure under point *e*.

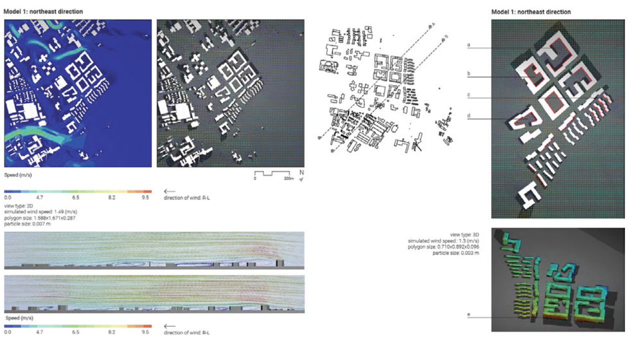

Figure 18-22. Wind power in bands (left) and vortex direction with vectors (right) / directions of airflows with cross section vectors - Example 0 - SW direction (left) NE direction (right), cross section

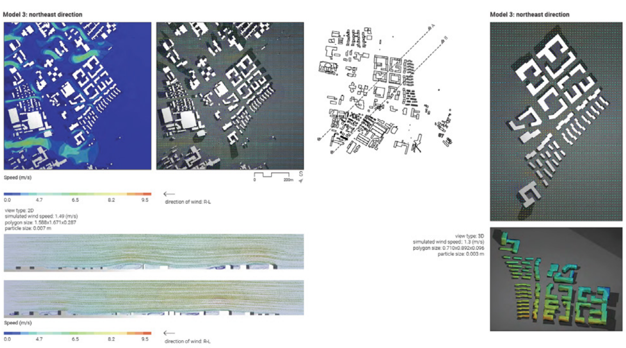

Figure 23-26. Wind power in bands (left) and vortex direction with vectors (right) / directions of airflows with cross section vectors - Example 0 - SW direction (left) NE direction (right), cross section

Using the previous test results of Model 1, I adapted it with new breakthroughs in the north-south direction, by shifting the lamellar layout of the row houses to an arrangement, which directs the currents of the NE winds and applied a terraced and articulated facade of the northern building blocks. The breakthroughs along with terraces reduced the outflow and turbulence, but there was still room for improvement. The southwest wind again shows similar effect to the northeast direction. A dead zone appears under point *a* as is the case with the SW wind direction. Point *e* shows improved conditions, as compared to the previous example.

The last design solution in Model 3 uses all of the findings from previous analyses, with the addition of new breakthroughs, new displacements and further subdivisions of the facades of the northern part of the neighbourhood. The building blocks with a stepped north wall show a great improvement, which was used again in the interior neighbourhoods. It appears that the use of breakthrough configurations on complex morphological configurations works well in redirecting flows and redistributing wind loads. That methodology should be tested further on the case of other urban areas. The simulation are oriented towards a better understanding of urban aerodynamics. For more accurate results, especially regarding the impact of individual building typologies on turbulence and the air currents and understanding of each other effects, would require complex computational studies that would include analysis of the non-negligible effects of micro urban heating of thermal currents, the braking forces or the "roughness" of buildings, and above all, a more rigorous analysis of the 3D side effects of a horseshoe vortex. Detailed analyses are described in the study of flows and turbulence urban canyons [12].

5. Discussion

The purpose of the article was to provide more accurate and clearer results, but the work was limited primarily by the availability of a more powerful software. I try to justify the missing calculations of wind dynamics by referencing recognized wind studies made international researchers. The distribution of the wind velocity field is highly dependent on the topography of the area and has different characteristics, depending on the wind direction and the use of morphological models on the project.

The main finding of the assignment is that the building elements in the wind-flow simulation analysis exhibited a variety of ventilation capabilities. The indirect findings of the article show the many possibilities of adaptation of building modules in urban design that can achieve changes in the urban microclimate and damp its negative effects - the findings are linked to the urban layout with a prevailing building block configuration, which are placed perpendiculary to the direction of the perceived prevailing winds. This can be done by: (a) adjusting the height of the buildings, depending on the distance between them; (b) forming a profile to the wind-exposed building facade in all directions (upper and lateral edges); (c) by making breakthroughs in transversely erected buildings; (d) using suitable plant species and organizing the landscaping. The built area is suited for a design with relatively high density and a questionable layout of some building-masses that are positioned transversely to the wind direction. In doing so, it is important to point out that the purpose of the project was to adapt the baseline urban plan of the neighbourhood in a way that was more environmentally acceptable in maintaining the existing positive features of the site and in ensuring adequate climatic conditions within the neighbourhood. It is possible to partially balance the negative effects of the proposed urban design with inserting breakthroughs, however transverse high construction higher than six floors should still be avoided in the area, as each additional floor reduces the ability to ventilate the inner urban spaces and increases the effect of turbulence. The grid structure of roads and ventilation corridors in the north-south direction should also be protected.

The process of working on the analysis of prevailing winds while also developing an urban masterplan is demanding and, in my opinion, also impractical for everyday use in project work. Such work of resolving wind dynamics in the urban environment is, for the time being, particularly limiting in terms of accessibility of meteorological station data. The choice of the project was contingent on the availability of data from the Bežigrad Weather Station. Otherwise, the data of this magnitude is available exclusively at selected weather stations across the country, or more so at airport weather stations.

The advantage of using wind modelling can be seen in further development of the theoretical foundations of wind dynamics and in the careful testing of building modules that could serve as technical design manuals, possibly in establishing criteria for creating comprehensive quality models of morphological patterns of the future. General wind maps at the settlement level are expensive and time-consuming, but they are certainly useful and have their place in the development of urban plans, municipal spatial planning documents and in the preparation of professional meteorological documents. Their usefulness is verified and important in deciding on the intended use of land according to macro and microclimatic conditions, exemplifying the spatial plans and strategies of cities. The guidelines can ease the work of architects and planners, since the best-case scenarios and site configurations could in theory be already discussed and decided on in advanced.

6. Conclusions

The use simulation wind-analysis is entirely reasonable in search of proper functioning of the new spatial interventions, or in using building typologies that have already shown decent environmental performance. The results of the analytical part of the article showed that distribution of wind velocity field is highly dependent on the built area and has different characteristics depending on wind directions and the use of morphological models on the project. The main finding of the article is that the building blocks showed a diverse ability to achieve ventilation, considering of their morphological configuration. An indirect finding of the task shows that there are many ways to adapt building modules in urban design and attain changes in the urban microclimate and to balance its negative effects. The findings are related to the urban design with positioning perpendicular to the direction of the perceived prevailing winds.

Acknowledgments

The research is secondary to the master thesis entitled: “The use of wind modelling in urban design in the case of the project site Novi Bežigrad in Ljubljana”.

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