Wind Analysis Methods to Improve Pedestrian Comfort in Urban Design

A case study in Tallinn, Estonia

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Urban microclimate plays a significant role in enhancing human health and well-being in urban areas. We present a method for cooperation between architects and urban climate experts to evaluate and design the best planning proposal for a case study in a high-rise district of Maakri, Tallinn, Estonia. The method investigates two seasons for pedestrian wind comfort evaluation - winter and summer. Also, reducing the number of simulated wind directions based on the hourly wind data shows reliable initial results, saving computational resources. Final urban planning proposal presented in the study shows improvement in the pedestrian wind comfort of the district.

Keywords: *Computational Fluid Dynamics (CFD), Pedestrian Wind Comfort, Urban Planning, Design Evaluation, Lawson Comfort Criteria*

INTRODUCTION

Wind comfort is crucial for enhancing the safety, accessibility and livability of open urban areas (Yang et al., 2023). City dwellers spend plenty of time outdoors and need a pleasant environment for recreational purposes. Pedestrian wind comfort assessment is a beneficial and significant way of evaluating, improving and creating comfortable outdoor spaces (Moonen et al., 2012).

Buildings modify airflow patterns, leading to physical discomfort for pedestrians. Factors such as the height, size, location, and shape of buildings and urban features like parks and greeneries greatly influence the acceleration or reduction of wind effects. To avoid the creation of uncomfortable or even unsafe urban spaces, microclimate assessment should be taken into account in the early stages of urban design (Erell, Pearlmutter and Williamson, 2011). This leads to assessing several design solutions simultaneously or during a short period, creating a demand for high computational resources, expert knowledge and time. In this research, we attempt to develop a novel, efficient and accurate method to evaluate initial pedestrian wind comfort through simulations, allowing architects and urban planners to validate the design throughout the way and make decisions based also on microclimatic conditions.

The focus of this method lies in investigating two seasons – winter and summer – separately. During winter, mitigating urban winds is crucial to decrease thermal discomfort due to wind chill. During summer, urban design solutions should promote airflow to enhance thermal comfort. This study also investigates a method to perform faster wind analysis. The novelty of this method lies in assessing pedestrian wind comfort using only prevailing wind directions for each season, based on the occurrence frequency. To validate this method, we conducted an annual wind comfort analysis using 16 wind

direction simulations and compared the results with an analysis using a smaller number of wind direction simulations through the coefficient of determination R^2.

The urban planning competition in Maakri district, Tallinn, Estonia, serves as a case study. According to the architectural competition brief (*Eesti Arhitektide Liit – Maakri kvartali arhitektuurivõistlus*, no date), the aim was to achieve the best urban space solution in terms of public space quality. Currently, in the middle of the district, a parking lot should be redeveloped into an active, open, attractive and pedestrian-friendly park surrounded by several new high-rise building developments. Together with architects and urban planners, we propose a design solution for the competition and validate a new method to evaluate pedestrian wind comfort.

The significance of this research lies in tackling two inherent challenges faced by researchers and designers when improving pedestrian wind comfort: the whole year validation of solutions, and the shortening of computation time while guaranteeing accuracy of results. Thus, the research presents a problem-solving approach developing a computational workflow to analyse seasonal wind comfort and a method for selecting and using a limited number of wind direction simulations.

METHODS

The aim of this research was to develop a fast and reliable pedestrian wind comfort assessment method and evaluate an urban planning case, assisting architects and urban planners with designing of a new high-rise building complex. First, we introduced architects to how new building developments influence wind flow dynamics. Throughout the work, we assisted them with comments and solutions, evaluating multiple planning variations in the process. This article presents the final design for the competition compared to the current situation in the district.

The proposed urban planning solution was investigated during two seasons – winter and summer. During winter, in addition to providing wind comfort, it is important to mitigate urban winds to decrease thermal discomfort, also called wind chill (Kim, Lee and Kim, 2018). During summer, urban design solutions should promote airflow to enhance thermal comfort and reduce heat stress while still considering pedestrian wind comfort levels. As the winter season, we considered the time from 8 to 18 in the months from December to March (temperatures below 0°C). For the summer season, we considered the time from 8 to 20 in the months from May to September (temperatures above 20°C).

We conducted a 16 wind direction simulation and used the coefficient of determination (R^2), showing a strong correlation of the results to validate using only 50% of the hourly wind data for each season. The number of minimum wind directions required to assess half of the meteorological wind data was calculated for each season separately. We analysed the meteorological data obtained from (Lawrie and Crawley, 2022) using the Ladybug Tools plugin for Grasshopper (Ladybug Tools LLC, 2022). Hourly wind velocities were sorted into 16 wind directions (starting from 0°, every 22.5° clockwise), allowing us to order the directions based on the percentile of occurring frequency and select the prevailing ones.

Wind Simulations and Comfort Maps

We used the Eddy3D Grasshopper plugin (*Eddy3D*, 2018) to perform computational fluid dynamics simulations (Kastner and Dogan, 2022). The plugin uses a cylindrical domain in OpenFoam software for an annual multiple wind direction simulation (Kastner and Dogan, 2020). For this research method, two 3D building models were created in Rhino using the Estonian 3D twin (*Ehitisregister*, 2015). The first model is a simplified version of the existing situation in the district (figure 1a).

We excluded sloped roofs, trees and canopies to shorten the computational time. Since the difference in terrain heights in the area is around 5 m, we also modeled a simplified terrain. The second model with the final design solution included three new high-rise buildings and modifications in the terrain (figure 1b).

Since the size of a cylindrical simulation domain (Kastner and Dogan, 2020) depends on the tallest building in the model, it was different for two simulations. In the existing situation 3D model, the tallest building is 116 m high, placed on the terrain (5 m), so the total height is 121 m (H_{max}). The height of the cylindrical domain was set to 726 m ($6 \times H_{max}$). The size of the outer radius was 4445 m. In the final design solution, the tallest building was one of the proposed new developments with a total height of 127 m. A cylindrical domain for the second simulation was 762 m high and with an outer radius of 4535 m. We used 5 m/s (U_{ref}) at the height of 10 m (z_{ref}), and the aerodynamic roughness length (z_0) as 1 (city environment). Inside the district in the designated competition area, we created a grid 3×3 m at a height of 1.5 m to evaluate pedestrian wind comfort in each point (figure 2).

Wind comfort maps were produced using the Lawson 2001 wind comfort criteria (Girin, 2020). The criteria defines comfort activity categories based on wind velocities and time exceedance (Janssen, Blocken and Van Hooff, 2013). Each category of the criteria is associated with an outdoor activity (table 1). The most comfortable – category 1 – is acceptable for frequent sitting, such as terraces for restaurants and cafes. Category 2 is suitable for occasional outdoor seating, playgrounds. Category 3 is meant for entrances, transport hubs and small kiosks, where people do not spend much time. Areas in category 4 are acceptable for walking or cycling. Category 5 is uncomfortable for any outdoor pedestrian activity (De Luca, 2019). The main targets for wind comfort were eliminating Lawson level 5, minimizing levels 2-4, maximizing level 1 for winter; and eliminating level 5, minimizing level 4 and maximizing levels 1-3 for summer.

Figure 1
Maakri district 3D model: a) existing urban layout; b) competition proposal design

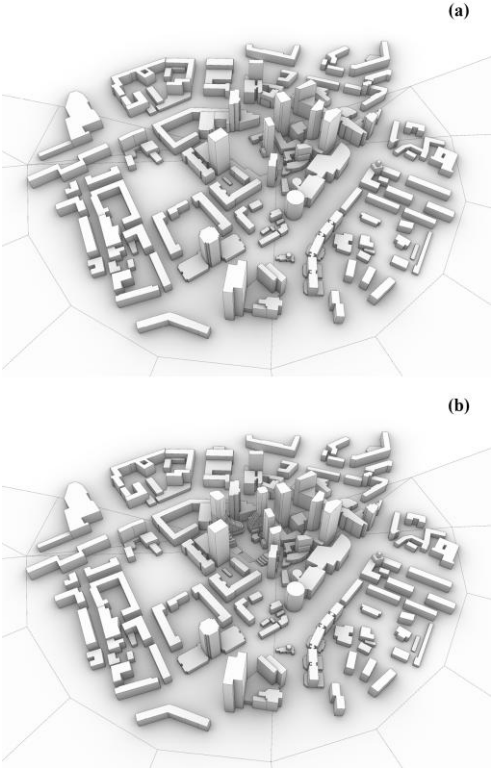


Table 1
Lawson 2001 comfort criteria

Wind velocity	Time exceedance	Comfort activity
> 4 m/s	< 5%	1) Frequent sitting
> 6 m/s	< 5%	2) Occasional sitting
> 8 m/s	< 5%	3) Standing
>10m/s	< 5%	4) Walking
>10m/s	> 5%	5) Uncomfortable

RESULTS

It is recommended to use 8 to 16 wind directions for a simulation as a general guideline (Kastner and Dogan, 2022).

Conducting and evaluating a 16 wind direction simulation for each proposed urban planning solution requires time and computational resources. To optimize the process, we initially assessed the current situation in the Maakri district. This assessment determined the percentile of hourly wind data and the minimum number of main wind directions for creating a fast and reliable initial pedestrian wind comfort analysis.

Selection of Wind Directions for Seasonal Analysis

We analysed annual meteorological data of Tallinn, Estonia and derived 50% of the hourly wind data. Prevailing wind directions necessary to select 55,5% of the hourly wind data are 180°, 202.5°, 225°, 270° and 247.5°. Figure 2 presents two wind comfort maps created using 16 and 5 wind directions and the correlation based on the comfort level of every grid cell. Two pedestrian wind comfort maps present similar results regarding pedestrian wind comfort. We used the correlation of the comfort level of each individual grid cell between the 16 wind directions and 5 wind directions (55,5% h) to understand how the levels of each comfort category are distributed. The coefficient of determination showed a fairly strong correlation (R^2 = 0.79), and we decided to conduct the seasonal simulation using also 50% of the hourly wind data.

For each season, we analysed the main wind directions in the climate data for Tallinn, Estonia. During winter, the prevailing wind directions are south-southeast (157,5°), south (180°), south-southwest (202,5°) and southwest (225°). These four wind directions are necessary to select 58,7% of the hourly wind data. During summer, the prevailing wind directions are south-southwest (202,5°), southwest (225°), west-southwest (247,5°), west (270°) and northwest (315°). Selecting these five wind directions covers 49,8% of the hourly wind data. Figure 3 presents wind roses for the winter and summer seasons.

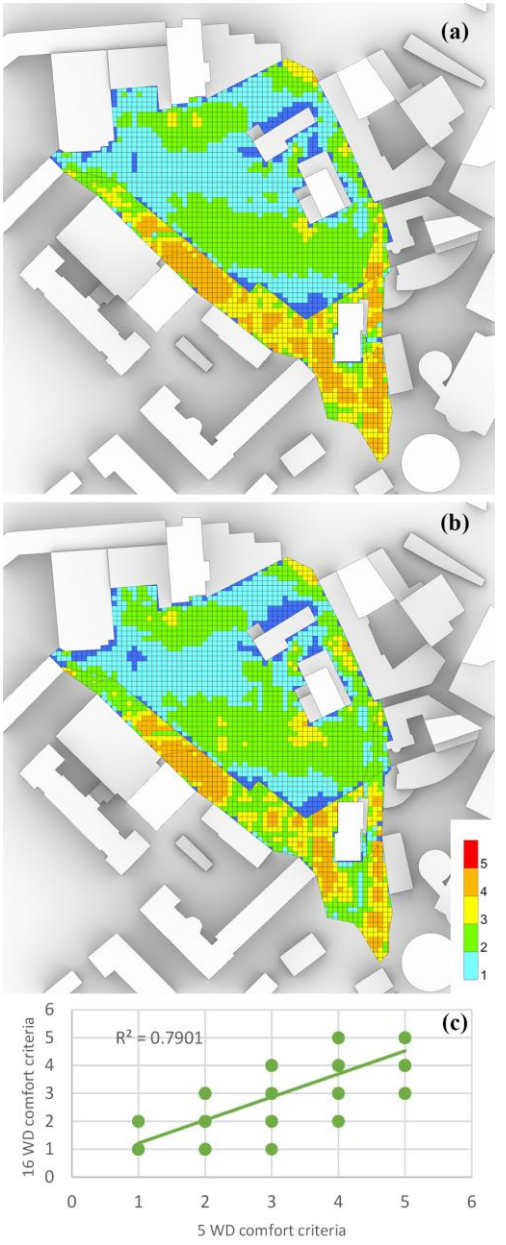


Figure 2
Pedestrian wind comfort maps obtained using a) 16 and b) 5 wind directions. The color legend defines comfort categories according to Lawson 2001 comfort criteria: 1 = frequent sitting; 2 = occasional sitting; 3 = standing; 4 = walking; 5 = uncomfortable. c) correlations between 16 and 5 wind directions based on the comfort level in each grid cell.

Figure 3
Wind roses for Tallinn, Estonia.
a) winter season,
b) summer season

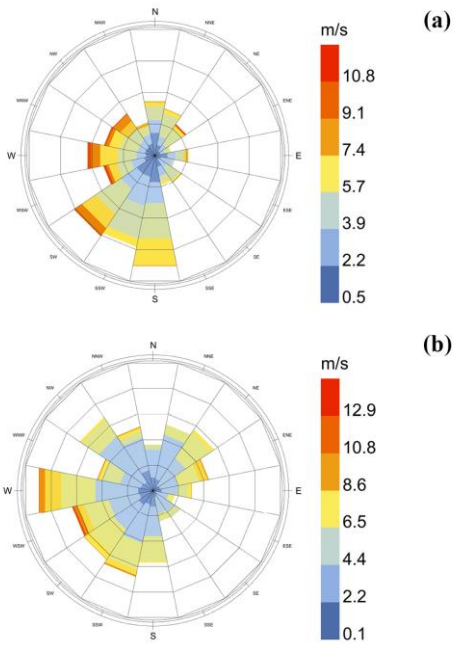
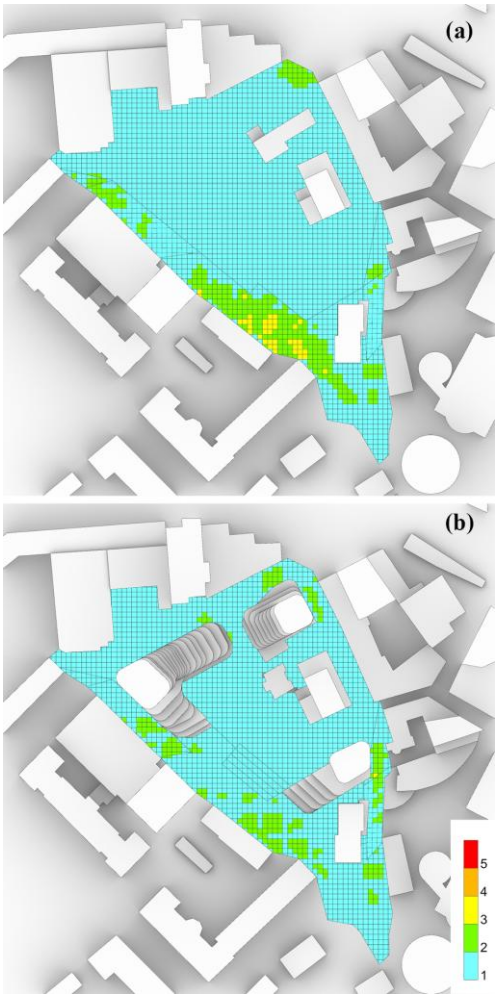


Figure 4
Pedestrian wind comfort during winter season
a) existing situation
b) competition planning design proposal



For the final seasonal design evaluation, we conducted a simulation using seven wind directions (4 for the winter and 5 for the summer, four of which overlap).

Seasonal Wind Comfort

Winter season assessment results showed improvement of the existing situation by realising the proposed urban planning solution (figure 4 and table 2). Areas in comfort level category 3 (good for standing, entrances and bus stops) transformed into areas comfortable for occasional seating (category 2), since new buildings block wind and it does not accelerate. During winter the wind velocities reach up to 3,4 m/s in the existing scenario, and proposed solution reduces the velocity to 2,7 m/s.

Summer season assessment (figure 5, table 3) also shows improvement, since faster airflow increases thermal comfort reducing heat stress.

Table 2
Percentage of area in each comfort category during winter

Winter comfort level assessment		
Comfort category	Existing situation (%)	Proposed solution (%)
1	87.67	91.91
2	10.95	8.05
3	1.39	0.04
4	0	0
5	0	0

The areas in comfort category 5 (uncomfortable) are located outside the proposed recreational park area and are mainly occupied by car roads. Pedestrian passages near these areas were designed to be protected by adding greenery and windshields. Architects were provided with wind vector maps of the area, indicating the wind direction that needed implementing mitigation strategies. During summer evaluation, simulation showed 5,6 m/s as the strongest wind velocity in the existing situation, and 5,7 m/s in the proposed design.

In the proposed design solution, the park area is in the middle of the new development, creating a comfortable and inviting urban space. In both seasons, the park area is mostly comfort category 1, suitable for all activities.

We provided the architects with detailed recommendations used for the design:

Areas with level 5 (red) – wind comfort conditions not acceptable for every activity. Architects sheltered these areas mostly with vertical (and in case horizontal) light structures and/or dense evergreen vegetation after analysing the direction of the wind vectors for every season that presents level 5 wind discomfort. As a second option, these areas were made not accessible for pedestrians, for example, by placing vegetation like shrubs, fountains, etc.

Areas with level 4 (orange) – wind comfort conditions acceptable only for "business walking or cycling". Activities of "walking" (level 3) were designed, providing shelter from the winter wind directions.

Areas with level 3 (yellow) – wind comfort conditions acceptable for activities of "walking" (+ activities of level 4). Activities of "standing" (level 2) were designed providing shelter for the winter wind directions.

Areas with level 2 (green) – wind comfort conditions acceptable for activities of "standing" (+ activities of level 3 and 4). Activities of "seating" (level 1) were designed providing shelter for the winter wind directions.

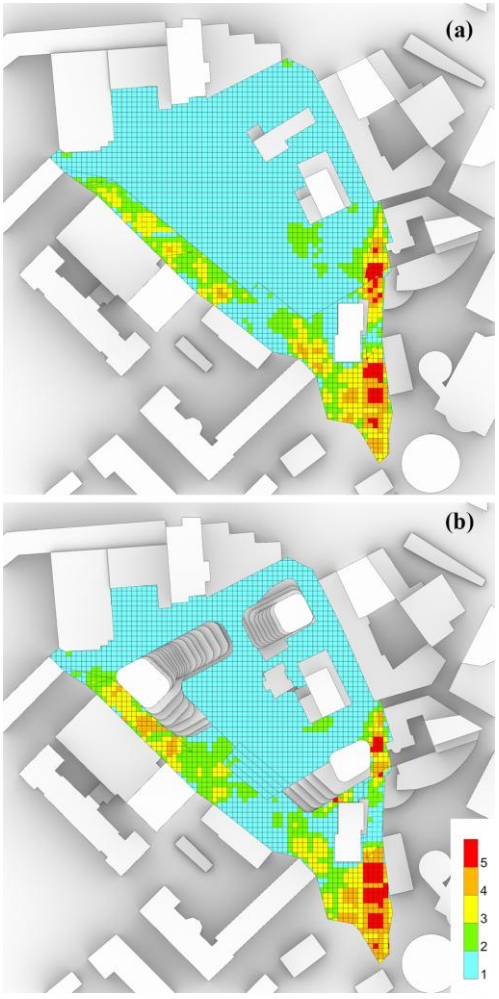


Figure 5
Pedestrian wind comfort during winter season a) existing situation b) competition planning design proposal

Summer comfort level assessment		
Comfort category	Existing situation (%)	Proposed solution (%)
1	71.68	71.09
2	13.04	13.32
3	9.81	8.68
4	3.84	4.76
5	1.63	2.14

Table 3
Percentage of area in each comfort category during summer

Areas with level 1 (light blue) – wind comfort conditions are acceptable for activities of "seating" (+ activities of level 2, 3 and 4).

Figure 6 presents final design visualization of the urban development created by the architects.

Figure 6
Design visualization of the new urban development

CONCLUSION

In this research paper, we show a method of evaluating pedestrian wind comfort seasonally, promoting different activities for the winter and summer seasons. The collaboration with the architects allowed us to evaluate a real case scenario and propose solutions to improve pedestrian wind comfort in the high-rise urban district.

We used meteorological data of Tallinn, Estonia and reduced the number of simulated wind directions to 50% of hourly wind data for each season, in contrast to the conventional 16 wind directions (Hågbo and Giljarhus, 2024). This allowed us to evaluate multiple design solutions and save on computational resources and calculation time and implement the evaluation of pedestrian wind comfort into the early urban planning stage (Erell, Pearlmutter and Williamson, 2011). We used Eddy 3D plugin (Kastner and Dogan, 2022) to conduct simulations.

The results show that the proposed planning solution improves the pedestrian wind comfort of the area, mitigating the wind during the winter season and allowing airflow during the summer. During the winter season, maximum wind velocity in the area decreases from 3,4 m/s to 2,7 m/s. This leads to the improvement of comfort levels in the area – category 1 gains 4% from categories 2 and 3, which allows architects to design various outdoor winter activities in the area.

During the summer season, wind was accelerated from a maximum wind speed of 5,6 m/s to 5,7 m/s, promoting airflow and mitigating heat stress. The areas in comfort category 4 (walking) and 5 (uncomfortable) are mainly located on the car roads, and pedestrian streets near are protected with vegetation or wind shields.

The research investigated a high-rise urban district in the city centre of Tallinn, Estonia. Different meteorological data and urban environments could require a different number of minimum required wind directions. We plan to expand the research and test the usability of the proposed method in diverse urban settings.

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