The role of building morphology on pedestrian level comfort in Northern climate

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Abstract. Due to the rapid densification of cities, improving outdoor comfort is becoming increasingly important. To address this need, the current study introduces a methodology to evaluate outdoor comfort in the proximity of typical buildings in Tallinn, Estonia. The microclimate simulation software ENVI-met was employed to investigate the outdoor comfort conditions. The research outcomes show that the building's form, height, density, and orientation change consistently the pedestrian comfort around the buildings. The findings suggest that the integrated analysis of different building morphologies, massing, orientation, and their influences on the surrounding microclimate, thermal, and wind comfort are important.

Keywords: Urban climate, Thermal and wind comfort, Building morphology, Urban simulation

1. Introduction
After the 'Brundtland report' [1], sustainable development has become one of the main goals of urban policy-makers. Rapid densification of cities, and a high rate of energy consumption [2-4] encourage researchers to find solutions to meet the requirements of urban areas. Buildings create local microclimates that influence outdoor comfort [5-6]. Several studies in the last 30 years have focused on the wind effects in the urban canopy layer [7]. Urban morphology affects the climatic factors, which in turn determine the outdoor thermal comfort [8]. Although there is a strong interest in the quality of open urban spaces among urban designers and users [9], thermal comfort seems to be neglected in many building requirements and in most of the studies. Thus, there is unexplored potential investigating optimal urban morphologies for outdoor comfort to help implementing conscious design and planning practice [10].

The main aim of this study is to investigate the performance of different building morphologies on the thermal comfort and wind comfort of pedestrians, in the city of Tallinn, characterized by a humid continental climate. In the study, the correlations between the climatic factors determining outdoor thermal and wind comfort are evaluated in relation to the buildings’ features to help finding effective design parameters for enhancing the quality of outdoor life and pedestrians’ thermal comfort. The current study focuses on morphological features of buildings in Tallinn, Estonia (Lat. 59°26’N Lon. 24°45’E), with a humid continental climate according to the Köppen-Geiger classification Dfb [11].

2. Literature review
For a city to be “livable,” the focus should be on the comfort experience [12]. Outdoor comfort is an essential parameter to assess the quality of the urban microclimate and define guidelines for sustainable urban development, but it is a relatively new field in research [18]. Numerous studies have focused on the improvement of thermal comfort in outdoor spaces [3] [6] [9] [12]. Cohen et al., defined thermal
comfort as “the state of mind, which expresses satisfaction with the thermal environment” based on the ASHRAE standard [14]. Field studies like Nikolopoulou et al., combined microclimate measurements and surveys from pedestrians to evaluate thermal comfort through both objective and subjective factors [9] [15] [17]. Building morphology has consistent effects on the thermal environment [17]. Furthermore, Taleghani et al. showed which urban forms in the Netherlands can provide a more comfortable microclimate on the hottest day of the year [18]. Speed and direction of the wind vary considerably outdoor comfort, especially in urban areas, as expressed by Johansson et al [15]. Mittal et al., studied methods of assessing wind comfort at the pedestrian level through different wind comfort criteria, and their impacts on the architectural design [18]. The importance of wind for outdoor comfort is underlined by studies in different building morphologies on pedestrian level air flow [7]. Park et al., estimated wind speed using the ENVI-met model by using wind speed data [8].

3. Methodology and the assessment methods

In this paper, as a first step, building data is acquired analyzing GIS maps of the city of Tallinn, Estonia [23] (Lat. 59°26’N Lon. 24°45’E). Consequently, the forms of building are simplified and the typical buildings morphologies are categorized in accordance with existing literature. Then, building three-dimensional models are realized and simulations performed using ENVI-met to investigate thermal comfort and wind patterns. In the final step, outdoor thermal comfort and wind comfort are assessed, at the height of 1.1 meter from the ground, approximately the centre of the human body, on March 21, 10 am in Tallinn (Figure 1). The day has been chosen in as much it represents a worst-case scenario. March is the month with the highest average wind velocities and one of the coldest of the year (Figure 2), and March 21 at 10 am presents the highest hourly average wind velocity in the weather data file.

The outdoor thermal comfort is assessed using the PET thermal comfort index (°C) (Table 1), and wind comfort is assessed using the Lawson wind comfort criteria LDDC variant (Table 2), through the Wind Comfort Level (WCL) method [41].

| Range of the thermal index | Table 1: Predicted thermal perception by human [8]. |
|---------------------------|--------------------------------------------------|
| 4                         | Very cold                                        |
| 8                         | Cold                                             |
| 13                        | Slightly cool                                     |
| 18                        | Comfortable                                       |
| 23                        | Slightly warm                                     |
| 29                        | Warm                                             |
| 35                        | Hot                                              |
| 41                        | Very hot                                          |

| Comfort activity | Table 2: LDDC Lawson comfort criteria [19]. |
|------------------|---------------------------------------------|
| Sitting          | 4                                           |
| Standing         | 6                                           |
| Walking          | 8                                           |
| Business walking | 10                                          |
| Uncomfortable for all activities | >10 |

Figure 1. Computational workflow of the study

Figure 2. Wind velocity and temperature in Tallinn
ENVI-met is a microscale microclimate model based on the fundamental laws of fluid- and thermodynamics (Computational Fluid Dynamics model) and uses the Eulerian approach for the calculation of mass, momentum, and energy budgets [22]. Moreover, ENVI-met employs the microclimate in urban based on the principles of fluid mechanics [20], as Figure 3 shows [22].

**Figure 3.** A simple overview of the ENVI--met nesting, height of the simulated model, and grids [22].

The Lawson LDDC criteria define 5 activity comfort levels relative to wind velocities considering a 5% of time exceedance. The WCL method expresses the wind comfort of an area using a dimensionless number from 0 to 100 (all the area in the worst and best comfort level) obtained multiplying the areas (m²) relative to the comfort levels by weighting factors [22] and summing them. The results of the two assessments are used to investigate optimal building morphologies that guarantee higher pedestrian thermal and wind comfort. The ENVI-met environmental simulation software uses a microclimate model based on the fundamental laws of fluid- and thermodynamics.

### 3.1. Study area

According to the Tallinn City Council data, there are eight districts in the city [43]. Using the available data, a morphology classification of Tallinn’s building is done according to existing literature and methodologies [12]. Thus, ten morphologies are identified.

- **Block:** Compact square or rectangle with small difference between the size of the two sides.
- **Aggregated blocks:** Composed by the aggregation of few or several blocks without space between the blocks.
- **Linear:** This can be just a rectangle (4 sides) or an aggregation where there is a long rectangle that is predominant.
- **Series:** Between linear and aggregated block. A main rectangle and then other small blocks are aggregated all in the same way and size.
- **L-shape:** This can be a purely L shape made of two rectangles or have some small aggregations.
- **C-shape:** This can be a purely C shape made of three rectangles or have some small aggregations.
- **Articulated:** Different rectangles and blocks form a shape, far from a central part or where a central or main part is not recognizable.
- **Court:** These are large buildings with a block shape but with an open area in the center (that is important for microclimate).
- **Free-form:** Buildings with non-rectangular, curved and sometime aggregated shapes.
- **Cluster:** Made of separated buildings that form one single object or articulated buildings with many open spaces inside.

**Figure 4.** Tallin building morphologies
Table 3 shows the climatic condition and weather data of the simulation.

### Table 3: Weather data (Tallinn)

| Parameter                  | Value |
|----------------------------|-------|
| Wind speed (m/s)           | 8.40  |
| Wind direction (deg)       | 202   |
| Roughness                  | 0.010 |
| Dry Bulb Temperature (°C)  | 6.30  |
| Dew Point Temperature (°C) | 2     |
| Humidity (%)               | 74    |
| Direct Radiation (Wh/m²)   | 63    |

### Table 4: The definition of models.

| Morphology | Models | Floors | Density (m²) | Tallness (m) | Orientation |
|------------|--------|--------|--------------|--------------|-------------|
| Block      | M 1-170| 1-19   | 500-9500     | 3-57         | 0/20/40/60/80 |
| Aggregated block | M 171-340 | 1-19 | 500-9000     | 3-57         | 0/20/40/60/80 |
| Linear     | M 341-435 | 1-9  | 1000-9000    | 3-27         | 0/20/40/60/80 |
| Series     | M 436-530 | 1-9  | 1000-9000    | 3-27         | 0/20/40/60/80 |
| L shape 1  | M 531-625 | 1-9  | 1000-9000    | 3-27         | 0/20/40/60/80 |
| L shape 2  | M 626-720 | 1-9  | 1000-9000    | 3-27         | 0/20/40/60/80 |
| C shape    | M 721-815 | 1-9  | 1000-9000    | 3-27         | 0/20/40/60/80 |
| Articulated 1 | M 816-885 | 1-4  | 2000-8000    | 3-12         | 0/20/40/60/80 |
| Articulated 2 | M 856-895 | 1-4  | 2000-8000    | 3-12         | 0/20/40/60/80 |
| Court      | M 896-965 | 1-6  | 1500-9000    | 3-18         | 0/20/40/60/80 |
| Free form 1 | M966-1005 | 1-4  | 2000-8000    | 3-12         | 0/20/40/60/80 |
| Free form 2 | M1006-1045 | 1-4  | 2000-8000    | 3-12         | 0/20/40/60/80 |

The approach followed is to define models based on six variables. The variables of the study are morphological classes, number of floors and buildings, density, height, and different orientations.

### 4. Results and Discussion

As sidewalks are expanding to provide space for access to outdoor space, children playing, strollers, a growing population of older people and people of all ages just out for a walk [44], in this study, PET and wind speed were calculated on the sidewalk of every model, for a 4-meter perimeter surrounding the building at 1.1 m height. PET has been calculated on the basis of a number of parameters, like body and clothing parameters, and body metabolism as Table 5 shows. The next step is the evaluation wind comfort according to WCL, and based on the wind speed. The WCL criteria are considered the industry standard in the BREEAM and CIBSE recommend the guide [19].

### Table 5: Parameters in PET calculation

| Personal human parameters | Value |
|---------------------------|-------|
| Age of person (y)         | 35    |
| Gender                    | Male  |
| Weight (kg)               | 75.00 |
| Height (m)                | 1.75  |
| Static Clothing Insulation (clo) | 0.90 |
| Basal Rate (W)            | 84.49 |
| Work Metabolism (W)       | 80.00 |
| Calculate from walking speed (m/s) | 2.12 |

Finding simulation processes of different elements in the ENVI-met software environment allows a better understanding of the optimal results in terms of wind and thermal comfort on the 4-meter sidewalk around the buildings as Table 6 shows. Accordingly, Figure 5 shows an obvious result of PET and WCL wind comfort criteria in the studied cases. According to the scatter plot the horizontal axis shows PET in degrees Celsius, while the vertical axis is the WCL wind comfort criteria. In this study the thermal comfort of the models is in the range of moderate cold or extreme cold stress in the basis of the PET. According to the literature review and other studies, it was clear in advance that wind comfort and thermal comfort on the sidewalk of different buildings would vary depending on the characteristics of their surroundings and other elements.
Table 6. The optimum results due to the simulation process in ENVI-met environment

| Morphological class | Floor(s) | Area (m²) | Building (s) | Tallness (m) | Density (m²) | Orientation (degree) | WS | PET | WCL | Thermal comfort |
|---------------------|----------|-----------|--------------|--------------|--------------|----------------------|----|-----|-----|-----------------|
| M74                 | 15       | 500       | 1            | 45           | 7500         | 60                   | 1.22| 12.2| 85.29| Moderate cold stress |
| M86                 | 18       | 500       | 1            | 54           | 9000         | 0                    | 0.65| 12.8| 85.29| Moderate cold stress |
| M226                | 12       | 500       | 1            | 36           | 6000         | 0                    | 2.23| 12  | 85.29| Moderate cold stress |
| M236                | 14       | 500       | 1            | 42           | 7000         | 0                    | 2.23| 12  | 85.29| Moderate cold stress |
| M240                | 14       | 500       | 1            | 42           | 7000         | 80                   | 1.97| 12.2| 85.29| Moderate cold stress |
| M242                | 15       | 500       | 1            | 45           | 7500         | 20                   | 1.97| 12.2| 85.29| Moderate cold stress |
| M246                | 16       | 500       | 1            | 48           | 8000         | 0                    | 1.97| 12.2| 85.29| Moderate cold stress |
| M256                | 18       | 500       | 1            | 54           | 9000         | 0                    | 1.78| 12.2| 84.29| Moderate cold stress |

As Table 6 shows, the optimum PET and WCL wind comfort belong to the block and aggregated blocks classes, with a high number of 12-18 floors (12-18), and individual buildings with the highest heights between 36 and 54 m (36, 42, 45, 48 and 54). Thus, these morphologies of in the individual high-rise buildings provide better thermal conditions in the range of moderate cold stress load for pedestrians on the sidewalks of the buildings. Most of the best models are in 0-degree orientation, but the best performances have an orientation in 0, 20 and 80 degrees. In addition, in all the optimal models, the wind speed on the pedestrian level of the sidewalks decreased by about 2.5 m/s, while in the general weather data of March 21, used for the simulation, the wind speed was 8.4 m/s. In addition, the WCL wind comfort criteria in the lateral paths of these models are above 84% in the general view, which means that the morphological classes of the blocks and aggregated blocks provide more comfort and are suitable for all activities listed in Table 2. As the perception of thermal comfort around these classes of pavements are moderate cold stress (PET more than 12), individual buildings in the morphological classes of blocks and aggregated blocks in high-rise buildings cause more comfort perception in their peripheral areas, both in thermal and wind perception. According to the results, there is no obvious correlation between the number of floors, the number of buildings and WCL and PET. However, it is clear that models with a high number of floors and an individual building are better in guaranteeing thermal and wind comfort on sidewalks. In addition, models with the lowest thermal comfort, extreme cold load, and less than 80% WCL wind comfort criteria mostly belong to the classes Series, L-shape, C-shape, Free form, Court, and Articulated in the lower number of floors, with non-individual building in sites.

5. Conclusion

This paper provides information concerning the correlation between climatic factors, and building features that determine outdoor thermal and wind comfort. Due to the fact that outdoor activities in cities depend on the perception of thermal and wind comfort, some variables considered in this study can be effective in improving outdoor comfort in the northern climate of Tallinn, Estonia. In this study, data from more than 1000 models in ten morphological classes are derived and separately analyzed to achieve the morphology with the optimal thermal and wind comfort on the sidewalk around the building. The results showed that block and aggregated block create better comfort conditions in terms of thermal and wind comfort. The individual buildings in the high number of floors show the best performance. The results of thermal and wind comfort in sidewalks near buildings with the different morphological classes are trustworthy and valuable to use in the pre-planning, design and development of a city plan, to consider how morphology can change the comfort state in the city and which morphological classes are efficient to allow a wide range of activities.

Acknowledgment

"This work has been supported by the European Commission through the H2020 project Finest Twins (grant No. 856602)."
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