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Building Cluster Optimization to Integrate Energy Performance and Outdoor Thermal Comfort

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ABSTRACT
Climate change can be tackled by a careful design of urban density, buildings distance and orientation, and materials in order to pursue indoor and outdoor comfort, and low building energy consumption. The research develops a methodology to holistically coupling overheating risks, cooling energy consumption, and pedestrian comfort for the careful design of cluster configurations of office buildings in the city of Tallinn, Estonia. The outcomes can help climate conscious design in Nordic cities. Solutions are provided to reduce overheating up to 23.6% and to increase urban comfort up to 13.5%.

Author Keywords
Urban Design; Energy Efficiency; Urban Comfort; Environmental Analysis; Performance-driven Design.

ACM Classification Keywords
I.6 SIMULATION AND MODELING - Applications; J.5.

1 INTRODUCTION
Buildings form and distance, finishing materials and operation, as well as open spaces' sizes and materials affect local microclimate in cities. Urban morphology affects the magnitude of the meteorological parameters such as air temperature, relative humidity, wind velocity, and mean radiant temperature, which contribute in the definition of outdoor human comfort through thermal indices [6].

Also in Nordic cities, pedestrian thermal discomfort during the warm season is significantly increasing due to a lack of conscious design, especially in new commercial districts [5]. In the near future, urban fabrics will have an even more significant impact due to increasing global temperatures in the built environment. In office buildings characterized by glazed envelopes, the excess of solar gains and increasing exterior air temperature dramatically increases overheating and consequent cooling energy demand during the warm season also at northern latitudes [7]. Studies show the importance of surrounding buildings distance and urban layout in the design of energy efficient developments [8].

In this scenario, the choices of designers and planners can significantly improve both the livability of the urban environment and the quality of the urban microclimate [2].

The present work investigates the performance of office building clusters in Tallinn, Estonia, during the warm season. The aims are: 1) quantify overheating risk and cooling energy needed to maintain occupants comfort; 2) quantify pedestrian thermal stress in commercial districts; 3) find optimal cluster configurations for both performance and trade-offs. The scope is to provide design solutions to help increase the resource efficiency and urban comfort of commercial districts. The novelty of the work lies in the scarcity of overheating analysis for clusters of buildings and the lack of urban comfort studies in Estonia.

2 METHODS
Indoor and outdoor comfort are assessed using the Estonian energy ordinance [3], and the Universal Thermal Climate Index (UTCI) [1], respectively. The first requires that in offices, the temperature does not exceed 25 °C for more than 100 °C·h during the period from 01.06 to 31.08. The latter defines a comfortable condition between 9 and 26 °C equivalent temperature, and cold and hot stress levels.

2.1 Building Cluster
The office buildings cluster used in the study presents three tower buildings. Nine cluster layouts (V1-V9) are used to analyze variations of indoor temperature and cooling energy need, and outdoor comfort (Figure 1). The buildings

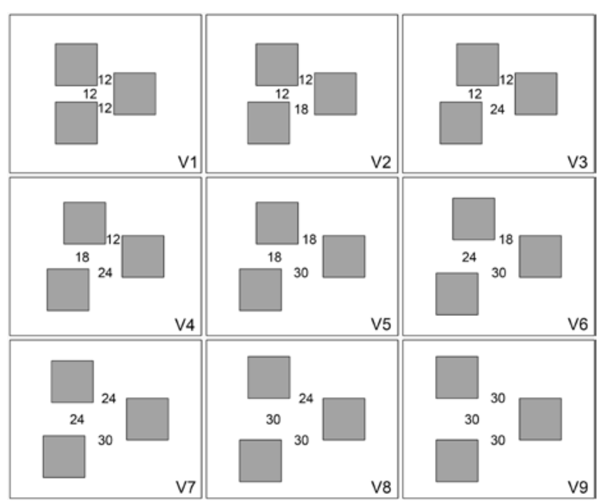


Figure 1. Cluster variations and figures of building distances (m).

Figure 2. The three urban areas of Liivalaia st., Mustamäe st. and Logi st. (left to right) with the building cluster plot (red rectangle).

square footprint length is 30 m, and the height is 100 m. The floor to floor height is 4 m for a total of 25 floors. The cluster plot is 138 m by 114 m in size. The building distances vary not uniformly from 12 m to 30 m (Figure 1). The nine configurations were chosen inasmuch representative of commercial district layouts recently built and under construction in Tallinn.

2.2 Urban Areas

The building clusters are located in three typical urban areas to evaluate the influence of different built environments on indoor and outdoor comfort. The area of Liivalaia st. is located in the high-density city center. The area of Mustamäe st. is located in a mixed-use and medium density quarter. The area of Logi st. is located by the sea in the low density port area. The plot is rotated differently in the three areas to follow the urban morphology (Figure 2).

2.3 Parametric Model

For the study, the three urban environments and the three cluster buildings are modeled using the software Rhinoceros. A parametric model is realized using the tool Grasshopper. It permits to change the location of the buildings for the nine configurations in each urban location (for a total of 27) and to run the following simulations and analysis automatically: 1) urban weather simulation using the Urban Weather Generator (UWG) software; 2) thermal and energy simulations using EnergyPlus software; 3) wind simulations using the software OpenFOAM through the plug-in Swift; 4) UTCI through the plug-in Honeybee.

2.4 Urban Weather

The way buildings are clustered together and anthropogenic activities define urban weather and the amount of heat trapped in urban canyons. UWG uses the urban morphology to calculate the average building height, the site coverage ratio and the façade-to-site ratio. Additionally, it accounts for traffic, building systems, and green areas. UWG permits to obtain weather datasets for the three urban areas through modification of the existing weather data collected in the rural area, to be used for thermal and UTCI analysis.

2.5 Overheating Simulations

Overheating assessment is performed for five floors for each office tower, 1^{st} (ground), 7^{th}, 13^{th}, 19^{th} and 25^{th} floor (Figure 3). The scope is to reduce the time for computationally intensive simulations, and at the same time to guarantee reliability of results. Each floor is divided into nine thermal zones, eight open offices on the perimeter and one core for a total of 135 zones. The use of multiple zones guarantees a minimum level of accuracy for interior and outer surface temperature simulations. Overheating results are analyzed only for the perimeter zones.

Parameters for the thermal zone, schedules and calculation methods follow the prescriptions of Estonian regulations [4]. Building envelope properties used are standard practice for energy efficient office buildings in Estonia (Table 1). Operable windows and natural ventilation are not used. Air temperature is simulated during the required period every occupied hour. The ordinance allows cooling in office buildings to provide indoor comfort, limiting the temperature exceeding 25 °C below 100 °C·h (degree/hour). The parametric model performs air temperature simulations

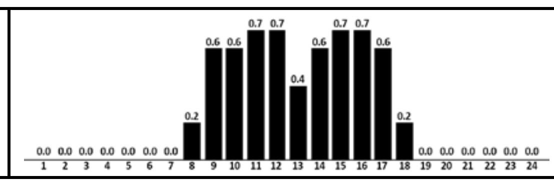
Thermal Zone Settings					
People density	0.059 (p/m^2)				
Equipment density	8 (W/m^2)				
Lighting power density	7 (W/m^2)				
Infiltration per floor area	0.000056 ($m^3/s/m^2$)				
Mech. vent. per floor area	0.002 ($m^3/s/m^2$)				
Shading/cooling set point	24/25 (°C)				
Building Envelope Properties					
	EW	Win	F	GF	R
U_t (W/m^2K)	0.15	0.9	A	0.16	0.12
Win	**WWR** 70% - **VT** 51% - **SHGC** 0.25				
Occupancy-Lighting-Equipment schedule					
Weekdays					
Weekend 1-24 0.0					

Table 1. Overheating simulation parameters. U_t=U value total, EW= ext. walls, Win= window, F=floors, GF=ground fl., R=roof, A=adiabatic, WWR=Win-to-Wall ratio, VT=visible transmittance.

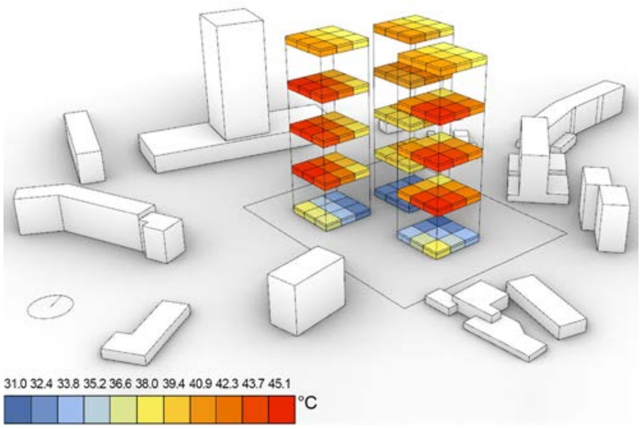


Figure 3. Floors used for overheating simulations for Liivalaia st. V5. Zone average temperature during analysis period.

with and without zone conditioning. Simulations without conditioning allow for determining indoor air temperature, those with conditioning estimate cooling energy demand to fulfil the Estonian energy ordinance.

2.6 Wind Simulations

Computational Fluids Dynamics (CFD) wind simulations are performed following best practices [4]. Buildings within a distance of 500 m from the plot are included in the computational domain. The size of the hexahedral cells varies from 16 m to 4 m for the urban area, 2 m for the surrounding buildings, 1 m for the cluster buildings and 0.5 m for the ground. Wind simulations are performed from 16 cardinal directions with a wind velocity of 5 m/s. Different terrain roughness values (Z_0) are used to account for the different urban morphologies at far distance from the plot.

2.7 Outdoor Comfort Analysis

UTCI assesses the temperature perceived by people based on meteorological input of radiation, air temperature, wind and humidity, and a physiological and a clothing model. The analysis period used is from 03.08 to 09.08. Being the Extreme Hot Week of the urban weather converted STAT file, it is used as a worst case scenario. The time selected is the business and after-work hours from 8 a.m. to 8 p.m.

The workflow used to calculate UTCI is the following. Mean Radiant Temperature (MRT) is calculated, taking into account direct solar radiation, urban environment, the buildings surface temperature and view factors from each of the 1448 nodes of the analysis grid. Building surface temperature is simulated using all the 25 floors of the cluster buildings with a single zone per floor, to limit computation time. Zone conditioning is used to simulate real building use. Hourly wind velocities are calculated multiplying the hourly measured wind speeds by wind factors obtained dividing the simulated velocities by the fixed velocity used for CFD simulations. Air temperature and relative humidity are obtained, as described in 2.4. The pavement material is concrete with a rough finish and an Albedo of 0.30. UTCI hourly values are recorded for every building cluster and every urban area (Figure 4).

3 RESULTS

Results show that temperature degree hour values in all variations and zones exceed by a large margin the maximum limit fixed, up to 168 times. Taking into account the configurations in the same cluster, degree hour increases with the buildings distance. In configuration V9 there is a variation of up to +21.4% in Liivalaia st., +16.4% in Mustamäe st. and +31.2% in Logi st. in comparison with configuration V1. This aspect affects the energy for cooling which in configuration V9 is up to +10% in Logi st. and up to +15% in Liivalaia st. and Mustamäe st. in comparison with configuration V1. The minimum and maximum zone energy need for cooling is 1.8 kWh/m^2 and 11 kWh/m^2. By comparing the same configurations in different districts, degree hour variations are up to +18.9% and +19.1% for clusters V8 and V9 respectively between Logi st. and Liivalaia st. This underlines the importance of the surrounding environment density for building performance.

For outdoor comfort assessment, building cluster variations are compared in relation to the maximum ratio of the outdoor area with no thermal stress (≤ 26 °C UTCI) during the analysis period. Evidence shows that also at northern latitudes urban discomfort is a serious concern since the maximum ratio of the area in the state of comfort ranges between 36.5% and 52.5% (Table 2). Results show an opposite trend comparing overheating. Cluster variations with more considerable buildings distance guarantee a larger comfort. Nevertheless, the smallest and largest plot area ratio in the state of comfort is not always related to V1 and V9, respectively. Additionally, the cluster variations with the worst and best performance are not the same in the different urban areas. The correlation between buildings distance and outdoor comfort is strong for the medium and low density areas and is weak for the high density area.

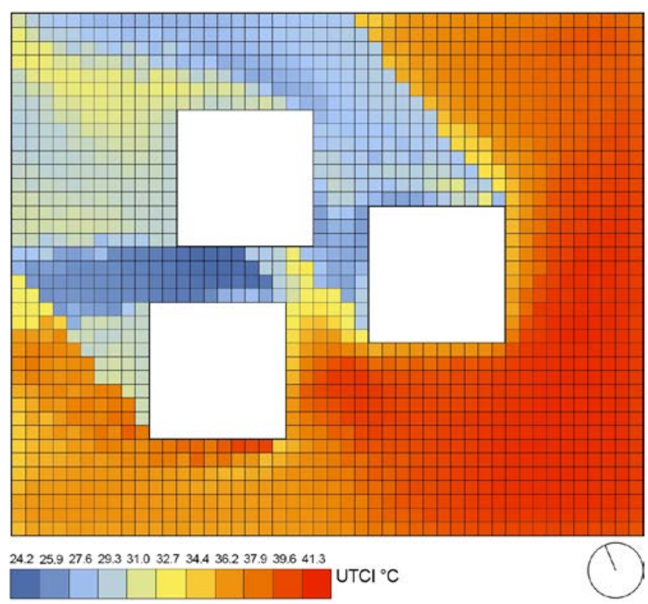


Figure 4. Outdoor comfort map showing UTCI (°C) values at 12 a.m. of the analysis day 04.08 for Mustamäe st. area V2.

V1	V2	V3	V4	V5	V6	V7	V8	V9
44.3	42.3	42.5	45.0	45.4	40.1	47.9	44.0	50.3
36.5	37.0	41.0	40.2	38.8	48.1	43.2	43.8	47.3
39.0	46.4	45.3	47.4	49.0	52.3	51.2	52.5	47.9

Table 2. Max. ratio (%) of plot area in comfort condition for Liivalaia st., Mustamäe st. and Logi st. (from top to bottom rows).

Analysis of integrated performance is performed using the minimum values of zone temperature degree hour, and the maximum ratio of cluster outdoor area with state of comfort. None of the three study areas presents an optimal cluster configuration. Nevertheless, trade-offs are present. (Figure 5). For Liivalaia st. area, variation V1 has the best performance for indoor comfort allowing the smallest overheating (4281 °C·h) and a mean value of maximum plot area with state of comfort (44.3%). For Mustamäe st. area trade-off variations are those with average mean values for both performances, as V3 (outdoor comfort 41% - overheating 5190 °C·h). For Logi st. area a trade-off is V5 that allows the maximum ratio of plot area with state of comfort (49%) and an average overheating (5594 °C·h).

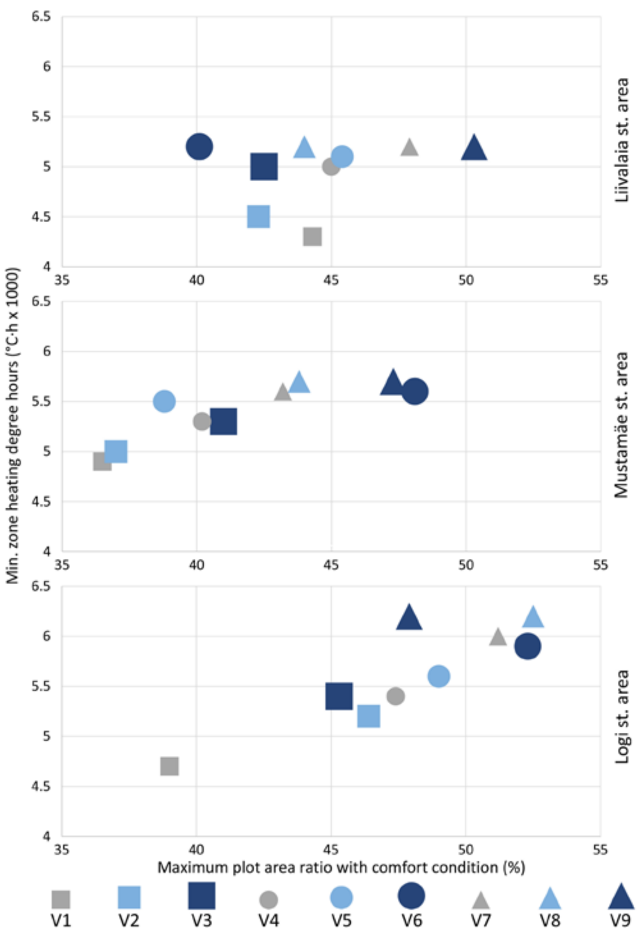


Figure 5. Charts of the integrated performance analysis.

4 CONCLUSION

The paper presents an integrated analysis of overheating and cooling energy, and outdoor thermal comfort during the warm season, for office building clusters located in three areas of the city of Tallinn. The study integrates the urban environment, cluster variations and different simulations in a parametric model. The outcomes of the study are: 1) All the building zones exceed the overheating limit by many times. It is possible to reduce overheating by up to 23.6% and cooling energy, through an environmentally conscious design; 2) Pedestrian thermal stress in commercial districts is a severe concern. The ratio of the pedestrian area within the state of comfort is no more than 52.5% during the analyzed period. It is possible to achieve an increase of 13.5% through performance-based design; 3) For the analyzed cases, no best configuration exists, but trade-off solutions are presented. These can be used by designers to increase the resource efficiency and outdoor comfort, hence to decrease the climate impact of commercial districts.

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