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Effect of the urban microenvironment on the indoor air temperature of the residential building stock in the Helsinki region

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ABSTRACT

Due to climate change, there is an increased risk of apartment overheating. In Nordic countries, heatwaves have not been common in the past and hence apartments are not equipped with mechanical cooling systems, so wise urban design might be a solution. This study evaluated the influence of the urban microenvironment on residential building indoor air temperature via green view index (GVI), floor area ratio and distance from the sea. We analyzed a large dataset of over 2000 apartments in the Helsinki region during summers of 2018 and 2021, where severe heatwaves were presented, and combined it with the aforementioned parameters. In the method used, closely situated buildings were clustered into groups by the microenvironment parameters. The results showed consistent correlations between clustered groups and microenvironment parameters, where the best-performing group had an indoor air temperature of about 1 °C lower than the average during the summers and 0.7 °C lower during the severe heatwaves. Building groups with higher GVI demonstrated a greater ability to endure long heatwaves, where combined influence of other urban microenvironment factors was significantly reduced. A substantial influence of sea distance and floor area ratio was observed during short heatwaves in the middle and late summer. The indoor temperature difference of the groups was compared to the average outdoor temperature difference of group areas based on the Finnish Meteorological Institute HARMONIE-AROME weather model implemented with the SURFEX module. The results revealed a consistent correlation between predicted outdoor and indoor temperatures and their distribution of group-to-area differences.

1. Introduction

Due to climate change extreme weather events are becoming more frequent and severe, resulting in local heatwaves and, subsequently, overheating of residential buildings [1,2]. The urbanization trend furthermore contributes to building overheating, thus rising the exposure of populations to heat stress worldwide [3,4]. This challenge is particularly critical since people spend up to 90% of their time indoors, with up to 50% of that time spent at home [5]. Overheating of residential building stock can adversely affect the quality of rest and health, especially during severe heatwaves [6,7].

Heatwaves account for premature deaths of vulnerable people throughout Europe, and create challenges even in Nordic countries [8–11]. Vulnerable people are most affected by overheating, so major heatwaves in recent decades have been evaluated to have caused about 200–400 excess deaths each in Finland [12–14]. The results showed that the heat-related mortality risk was substantially higher in Helsinki, an urbanized region, than the average in Finland, and the mortality rates attributable to four severe heatwaves (2003, 2010, 2014 and 2018) were about 2.5 times higher.

Studies predicting future climate in Finland indicate an increase in severe heatwaves in the coming years [15–17]. Mechanical cooling is not commonly implemented in the residential building stock, as the cooling period has been rather short, and the buildings are designed to have high insulation and airtightness due to cold weather conditions [18–22]. Because of this, in the summertime with extreme weather
conditions, buildings are less capable of dissipating heat during the night time if the outdoor environment temperature stays quite high. For instance, in the 2050 heatwave scenario, the maximum indoor temperature will exceed the health risk threshold value of 32 °C. It will bring about 3000 hours above 32 °C indoor temperature of building stock [23]. Another recent study of the building stock performance during the heatwaves of 2018 and 2021 showed apartment overheating, which has the most significant influence in the case of small apartments [24]. In addition, recent studies in Scandinavian climate highlighted the heat wave influence on the building stock, reducing its resilience [25]. Hence, it becomes essential to make buildings more resilient for hot summers and to prevent overheating even in Finland, which might be done by active or passive measures on the apartment, building or city level [26–29]. There are several main factors contributing to building stock overheating – weather (e.g. outdoor temperature, insolation direct and indirect and others) and such phenomena as the urban heat island (UHI) effect. The UHI, shows a correlation with urbanization, therefore large cities are more prone to high temperatures indoors [30–32]. Also, high direct and indirect solar radiation (solar insolation reflection), low urban vegetation level and high floor area ratio contribute to UHI [33,34]. The overheating risk, brought by UHI, could be prevented on the apartment or building level with passive measures e.g. solar shading, low g-value of windows and improved ventilation. Furthermore, cooling might also be provided on the district level with wise urban microenvironment design: urban vegetation, open water sources, low-emission building envelope materials and phase-changing materials [29]. Greenery (e.g. urban vegetation) and impervious surface area (ISA) (including built-up areas, pavements and roads) are the main factors. The ISA contributes to around 70% of all land-to-surface temperature (LST) variance [34–37]. It is reported that in the case of the 38 most populated cities in the US [38], where dark ISA (asphalt, concrete e.g.) increases LST difference up to 10 °C. The impact of greenery on mitigating the UHI effect mostly consists of re-emitting less energy due to evapotranspiration combined with reducing short-wave radiation [39–42]. The effect of the increase of land cover by increasing greenery on LST assessed in four Danish cities was lowering the temperature in about 4 °C [43]. In addition, the city greening strategy in Copenhagen reduced the impact of UHI and average outdoor temperature by around 2–3 °C [44]. Other studies show that passive measures on the district level, such as additional water sources, pools or fountains, decrease the outdoor temperature on average by around 2 °C, greenery might mitigate by an average of around 2 °C, shading and reflective building coating by 2.1 °C and the combination of the previous by 3.2 °C [45]. Moreover, UHI intensity is also impacted by seasonal variation due to changes in the amount of solar radiation and the metabolic activity of vegetation. UHI intensity is higher in spring and summer than in autumn and winter as spring and summer are often considered as growing seasons, and their LST temperature difference is higher by up to 5 °C [46]. The knowledge about the outdoor conditions, based on urban microenvironment factors provides an opportunity to understand the building stock performance. Nowadays for this purpose, city and weather simulation models are utilized. Weather models predicting the outdoor temperature are widely studied and there are various simulation models for describing the city conditions. Most of them are numerical studies based on the physical properties of buildings and street surfaces, and calculate the interaction of air and these surfaces [47–51]. The Finnish Meteorological Institute has used the high-resolution weather model, HARMONIE-AROME [45] to calculate outdoor conditions in Finnish cities. Implementations of the same model are used by 10 other European meteorological services to generate short-range weather forecasts [47]. The model takes into consideration physical atmospheric processes such as cloud microphysics and precipitation, radiative transfer, turbulence and shallow convection, which are parameterized within the model. In the latest model, the autonomous surface and soil module SURFEX is used to model the interactions between the atmosphere and underlying surfaces [52]. This model is able to produce a high-resolution distribution of outdoor conditions along the chosen region and thus might be used to calculate the building stock performance in building models, taking into account the influence of the urban microenvironment factors. To analyze the effect of the local microenvironment on the room conditions, there is a need to create a building performance model, such as an IDA ICE model [53]. The outdoor microenvironment conditions are now used as outdoor parameters. Also, models require comprehensive knowledge about the building, materials, systems in its construction and human behaviour as parameters for the calculation. This process requires creating a model of each building with its surroundings, if the model is scaled to city-level. The following step is to analyze the influence of the input parameters, such as urban microenvironment parameters, on the indoor air temperature. The process becomes data and resources demanding. Hence, understanding the influence of the urban microenvironment on building stock performance by traditional simulation techniques requires extensive knowledge, modelling and time for calculation. However, there is another approach to solving the task by using data-driven models or field measurements. Data analysis of field measurements requires a large database of building indoor conditions during a chosen period and knowledge of city urban microenvironment factors. Knowledge about greenery, building information, streets and roads, human behaviour and other parameters, as mentioned above, are essential also for it. Extensive knowledge about the region, building stock and weather is required. There are various studies conducted in North America, Continental Europe and the Middle East, as mentioned above, but only a few, such as the Copenhagen one, in the Nordic climate. The unique Nordic climate, characterized by its long, cold winters and relatively short, cool summers, demands a distinctive approach to prevent overheating in buildings. This creates a gap in understanding the influence of urban microenvironment factors on building stock indoor conditions for this specific region [33,37].

The novelty of this study comes from cross-correlation analysis of building indoor air temperature and urban microenvironment parameters in Nordic conditions during summer and severe heatwaves of 2018 and 2021 represented by a large dataset consisting of over 2000 apartments. For the analysis, we have chosen different periods: early summer, heatwaves and late summer to address seasonal ISA bias. We also compared the results of the analysis and indoor conditions to the results of the latest Finnish Meteorological Institute city and weather prediction model, based on HARMONE-AROME, to understand the overheating risks and deviation in outdoor temperature. The large database gives the opportunity to also implement local-based analysis, where an influence of urban microenvironment factors was distinguished from others by choosing close situated building groups with the same factors, averaging the influence of others. The green view index (GVI), floor area ratio and building location were chosen to represent urban microenvironment parameters. Knowledge about greenery and ISA is provided via previous studies about the GVI, building stock information [54–56] and information about water sources, which can predict more than 70% of temperature variation [37]. During past years, Helsinki encountered several heatwaves in 2018, 2020 and 2021 [57]. These factors create a unique opportunity to analyze the urban microenvironment factors effect on building stock indoor conditions. The effect of those parameters on indoor air temperature was calculated for the whole summer time and heatwave periods separately. The statistical influence was assessed with p-values, which indicated very strong or strong evidence. The mean indoor air temperature difference between the best and worst performing clustered groups according to urban microenvironment was also analyzed.

2. Methodology

2.1. Overview

In this study, 400 buildings with more than 2000 apartments in
Helsinki were chosen for analysis. In each building, from 3 to 6 apartments are equipped with indoor air temperature sensors. The sensors were located in a central location in the apartments, and thus their readings represent average room air temperatures. The hourly data was used for the years 2018 and 2021 and then analyzed building-wise to calculate the building mean indoor air temperature.

In Finland, the heatwaves were defined as hot days with a maximum hourly temperature above 25 °C. For this study, the years 2018 and 2021 were chosen as they had severe heatwaves and could be used to assess the effect of the local urban microenvironment in different regions of Helsinki. The heatwave influence was analyzed in four different time periods during the years 2018 and 2021: early summer, short and long heatwaves, and late summer. The correlation and weight factors of the urban microenvironment parameters were calculated and compared to assess the effect of local outdoor location on the room air temperatures in the different locations of the city. In this study, the local outdoor temperatures were also simulated in the same selected microenvironment regions previously described. The correlation between the room air temperatures and the outdoor simulated temperatures was analyzed.

The objective of this analysis was to study how well local outdoor temperature correlated with the local room air temperature in the same location when the effect of direct solar radiation through windows was neglected.

Based on the building’s location, additional information about the local urban microenvironment was obtained based on open sources:

- GVI (green view index) - the index was used to describe the level of vegetation on the sides of the street, the shading of trees and surrounding buildings at the height of 1–5 m.
- Floor area ratio - the index was used to describe the urbanization of areas and is a combination of average built-up area and the height of the buildings.
- Distance from the sea - this parameter reflects the effect of the seawater temperature on the local microenvironment.

Based on the obtained statistical data, GVI, floor area ratio and sea distance were statistically analyzed, and the values for those indices were selected for further analysis.

2.2. Apartment building stock data

More than 400 buildings in Helsinki were chosen for the analysis. The locations of those buildings are shown in Fig. 1. The construction year of the analyzed buildings varied from 1950 to 2010. All the buildings were apartment buildings of 3–9 floors. In each building, there were from 3 to 6 apartments, that were equipped with indoor air temperature sensors. Apartments were different in size: small (one and two-room apartments), and large (apartments with three or more rooms). Sensors were placed in central locations (main corridor) of the apartments where there was no exposure to direct solar radiation.

The room air temperature was recorded at intervals of 15 min for the years 2018 and 2021 with Airwits R2 devices (Table 1). The data points were then resampled into hourly mean data.

The data was filtered as follows:

- Excluded buildings with too low and too high mean indoor air temperatures for the summer period of 2018 and 2021 (below 18 °C and above 40 °C).
- Excluded buildings either having less than 85% of the data points for the whole period, or more than 3 consecutive missing hours.

After collecting initial temperature data, we addressed the measurements, which are always accompanied by errors that can affect the accuracy and reliability. We addressed both types: random and systematic. The random errors were addressed by averaging the measurements by time step, resampling the data to the chosen periods. The systematic errors were addressed by averaging and by using the temperature data differences, as the same type of devices with the same factory calibration was used [58]. Then the apartment data was calculated to the building level to mitigate the effect of the different apartment size, orientation or floor level, as each building had at least several apartments presented.

2.3. Weather data

Weather data from the Kumpula weather station was used for the years 2018 and 2021 [57]. These years had severe heatwaves, which

<table>
<thead>
<tr>
<th>Device name</th>
<th>Airwits R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy, temperature</td>
<td>0.2 K or ±1.5 % at 20 °C</td>
</tr>
<tr>
<td>Logging interval</td>
<td>15 min, resampled to 1 h</td>
</tr>
</tbody>
</table>

Table 1 Measuring device technical details.

Fig. 1. Building geographical distribution and weather station location.
were defined as continuous hot days with a maximum hourly outdoor temperature above 25 °C. The resulting outdoor air temperature distribution and heatwave periods are shown in Fig. 2 compared to the 2020 year, which is the average summer year for the past 30 years [24]. The data shows two main heatwaves for each year; a short heatwave of around 7 days, and then a longer one of around 16 days. These heatwave periods were chosen for analysis. The seasonal variation influenced the ISA, greenery and therefore UHI, and thus in addition, two other summer time periods for each year were chosen as references: early summer and late summer, as shown in Fig. 2. Thus, there were four resulting time periods for each year, selected for analysis:

- The first period was in the early summer, characterized by a transition from the spring season, resulting in the urban and natural environment temperature being lower than the air temperature.
- The second period was a short heat wave transitioning from normal summer temperature to warmer.
- The third period was a long heat wave in mid-summer after the first short heatwave. The urban environment and seawater were already warmed up.
- The fourth period was in late summer. The urban and natural environment was still warm after summer.

2.4. Urban microenvironment parameters

The green view index, floor area ratio and distance from the sea were chosen as representative parameters for this study. These urban microenvironment parameters were collected from articles and open sources [52,53,55]. For building analysis, we obtained the relevant parameter values and classified the buildings as either “high” or “low” based on whether their parameter values were within the highest or lowest 25% of the dataset.

This approach was preferred over 1 or 2 Sigma’s method due to the non-normal distribution of parameters and to clearly distinguish high and low levels while keeping as many results as possible. The buildings belonging to either 25 % lowest or 25 highest were clustered to form building groups, representing the average influence of allocated combinations of urban parameters, such as low or high GVI, floor area ratio, and sea distance. This grouping approach allowed us to minimize the impact of random factors on the buildings, such as construction year-based building thermal properties, ventilation airflow rate, and occupant behaviour.

2.4.1. Green view index

The GVI was chosen as it is able to describe up to 60% of temperature variations [33,59]. The values for indices were derived from the article [54] for the city of Helsinki. The data was presented in the form of points describing the index for a neighbourhood of city streets at a distance of 50 m from each other. Based on the data of the geolocation of buildings, the average value of the GVI for each building was calculated by the nearest single data point in 50 m. If there was more than 1 data point, then the average value was calculated by the 2 or 4 nearest data points.

Fig. 2. Daily maximum outdoor temperature distribution and the chosen four time periods in both years 2018 and 2021 and dashed line for 2020 average year.
which describe the line through the buildings geometrical centre or square around it.

The results are presented in Fig. 3, where the y-axis is the number of the building, the lower x-axis is the normalized distribution, and the upper x-axis is the specified value of GVI. The distribution of the index in the city of Helsinki showed a fairly high maximum value of 70 units and 34.2 on average, and this indicated relatively high greenery. It should be noted that the typical values for the cities were lower to around 25 on average in the literature [60–62]. All in all, the distribution of GVI was quite close to a normal distribution, however, some big cities are prone to have more area with low GVI, shifting the distribution left [62]. For further analysis, the value was normalized, where 1 = maximum, 71 units, and 0 = minimum, 11 units.

In this study, we determined that the value "high" had all the buildings above 45 (highest 25 %) and "low" – below 30 (lowest 25 %) correspondingly, as shown in Fig. 3.

2.4.2. Floor area ratio

The floor area ratio was chosen as it is able to describe about 12% of all temperature variations on average and up to 20% in cities [33]. The floor area ratio index was used to describe the urbanization of the areas analyzed, and it represents the average built-up area and the height of the buildings [55,63]. It described building’s floor area in relation to the size of the lot/parcel that the building is located on. In previous studies along with building density, it showed a significant effect on indoor air temperature in tropical climate up to around 4 °C [64].

We used data for Helsinki City, 2020 with a resolution of 100 m by 100 m, so the numerical value of the index was calculated based on the nearest grid cell from the geometric centre of the building [56]. The distribution of the index is shown in Fig. 4.

The top x-axis describes the floor area ratio which was quite low in Helsinki, with the mean of 0.42 corresponding to a single-entrance 6-storey building for a ground area square of 100 m by 100 m. The floor area ratio for big cities is mostly around 1.02–2.0, which is heavily dependent on population density and urbanization [65]. The buildings below 0.125 (one single-entrance 5-storey building per 100 × 100 m ground area square) have “low” parameter (lowest 25 %) and those above 0.6 (more than one two-entrance 5-storey buildings or one-entrance 9-storey building) “high” (25 % highest).

The bottom x-axis describes normalized values, where 1 = maximum, 2 units, and 0 = minimum, 0 units. The “low” was 0.2 and “high” was 0.6. In further analysis, we will use these normalized values.

2.4.3. Sea distance

In a previous study, it has been noticed a temperature gradient in the Uusimaa coastal region [66], where the difference in outdoor microenvironment temperature between coastal and land areas was around 1 °C. Studies in the United Arab Emirates showed an even more significant influence on the difference between LST near the coastline and away from the coast in summer up to 9 °C, showing that the cooling effect of the sea decreases as the distance increases [67]. Moreover, the distance from the coastline was found to be an important predictor of UHI in 42 French cities [68].

In our study, the distance from the buildings to the coast was calculated based on a digital map of the Baltic Sea coast [69], where the shortest distance was measured from the geometric centre of the building to the coastline.

On average, the sea distance was about 2.5 km, with the smallest being less than a kilometre and the largest just over 8 km. The distribution cannot be described as normal, as shown in Fig. 5. The bottom x-axis describes normalized values, where 1 = maximum, 8 km, and 0 = minimum, 0 km. The “low” was 0.2 and “high” was 0.6. In further analysis, we will use these normalized values.

The selected threshold values based on the distribution, so the value of 'high' (25 % highest) had all the buildings further than 6 km away and 'low' (25 % lowest) was closer than 2 km to the seashore.

In our experiment, we investigated the influence of three environmental factors - sea distance (SD), GVI and floor area ratio (FAR) - on the room air temperature. To ascertain the relationship between these factors and temperature, we employed correlation analysis, which is one of
the most common high-quality predictors [33] and then calculated as an effect in °C.

The same principle was utilized for the correlation analysis of the modelled outdoor temperature and indoor temperature of building group areas, where the result was represented by the correlation coefficient. These unitless correlation coefficients can range from −1, indicating a perfect negative linear relationship, to 1, indicating a perfect positive linear relationship, with 0 indicating no linear relationship between the variables.

Correlation analysis was performed to identify the strength and direction (positive or negative) of the relationship between the environmental factors. It enabled us to understand the degree of interdependence between the factors and their impact on temperature. By analyzing the correlation matrix, we could determine which factors had a substantial influence on temperature, and the extent of their influence.

2.7. Modelling of local outdoor temperature

The Finnish Meteorological Institute has applied the state-of-the-art high-resolution numerical weather model HARMONIE-AROME [45] to compute city outdoor conditions. The model is being developed for the purpose of generating short-range weather forecasts by the ACCORD consortium formed by 26 national meteorological services in Europe and the North. The HARMONIE-AROME model acknowledges and accounts for a broad range of physical atmospheric processes, including but not limited to cloud microphysics and precipitation patterns, radiative transfer, turbulence, and shallow convection, all of which were parameterized within the confines of the model. The non-hydrostatic, convection-permitting atmosphere model within HARMONIE-AROME supports a horizontal grid spacing down to hectometric scales. Details about HARMONIE-AROME are provided on the consortium [47].

An autonomous surface and soil module known as SURFEX (Surface Externalisée) [70] is specifically designed to simulate the interactions between the atmosphere and the Earth’s surface, covering different types of natural and anthropogenic surfaces including urban areas, forests, and oceans. Each of these four different surface types, or tiles, are handled within the model by their unique sub-model, and for urban areas this is done by the Town Energy Balance (TEB) model [71]. TEB follows the canyon approach, where the energy budget is calculated on three separate urban surfaces: roofs, walls and roads. The model takes
into account several physical processes occurring in an urban environment, such as 1) shortwave and longwave trapping effect of the canyon geometry; 2) anthropogenic sensible heat flux; 3) water and snow interception by the roads and roofs; 4) heat conduction and storage in buildings and roads; 5) interactions between canyon air and built surfaces [70].

Possessing the capability of generating high-resolution distributions of outdoor conditions for the selected region, this model is especially suited for calculating the performance of the building stock in architectural or civil engineering models. This includes accounting for the impact of various urban microenvironment factors.

The outdoor air temperature at 2 m above the ground used in the present study was extracted from short range forecasts modelled with HARMONIE-AROME cy43h2.1 [72]. The simulated data had a horizontal grid spacing of 750 m and covered Southern Finland during 2018 and 2021 summers (June to August).

3. Results

3.1. Clusterization of the buildings

Buildings were clustered in groups in the chosen Helsinki region, representing the effect of urban microenvironment parameters on indoor air temperature. These groups were selected to meet the condition of the most compact geographical positioning of buildings while adhering to the other criteria, mentioned above, shown in Fig. 6. After clustering, the smallest number of buildings in groups was 17, the largest was 29 and on average the group building count was above 19, which accounted for more than 800 apartments (data logging devices in the used dataset) in total, as presented in Table 3.

3.2. The correlation significance of microenvironment factors and indoor air temperature

The correlation of parameters with building groups average indoor air temperature for each period for most of the cases was high with p-values $<0.001$ indicating a very strong correlation. The correlation for the whole summer of 2018 and 2021 was also $<0.01$.

There were some outliers during some periods such as the GVI index during the early summer of 2018 having a p-value above 0.05. However, during other time periods and the year 2021, the p-value was lower so the results can be considered statistically valid. Thus the correlation combination of GVI: FAR and SD: GVI during 2018 with a significance of 0.03 on average too, as values between 0.01 and 0.05 show strong to moderate evidence, as shown in Table 5.

3.3. The influence of microenvironment factors during the whole summer

The effect of the urban microenvironment parameters on room air temperature was analyzed. In the analysis, the performance of the different building groups was compared with the best-performing group that had the coldest room air temperature. The results of the analysis are presented in Fig. 7 and Table 4. The difference in the average room air temperatures for the whole summer periods of 2018 and 2021 are shown. The results are presented in spider charts to show the consistency of building group performance as a visual profile, where zero represents the reference point of the coolest building group. The other groups are compared with that group.

The maximum temperature difference was about $1.2 \degree C$ between the coolest and warmest groups. The group with the lowest temperature had high GVI, high sea distance and low floor area ratio. The group with the highest temperature had low GVI, low sea distance and high floor area ratio. The high GVI had the most significant effect, reducing the indoor temperature on average by $0.37 \degree C$ for 2018 and by $0.21 \degree C$ for 2021. Low GVI increased the temperature on average by $0.12 \degree C$ for 2018 and

![Fig. 6. Geographical locations of the building groups that were clustered with green view index, sea distance and floor area ratio. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image-url)

<table>
<thead>
<tr>
<th>Acronyms of Clustered Groups</th>
<th>Sea distance</th>
<th>Green view index</th>
<th>Floor area ratio</th>
<th>Number of buildings</th>
<th>Number of apartments</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSDHGVHAR</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>29</td>
<td>112</td>
</tr>
<tr>
<td>HSDLGVILFAR</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>17</td>
<td>73</td>
</tr>
<tr>
<td>HSDHGVLHAR</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>17</td>
<td>77</td>
</tr>
<tr>
<td>LSDLGVILFAR</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>18</td>
<td>91</td>
</tr>
<tr>
<td>LSDLGVHAR</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>19</td>
<td>102</td>
</tr>
<tr>
<td>LSDLGVVHAR</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>17</td>
<td>82</td>
</tr>
<tr>
<td>LSDLGVILFAR</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>20</td>
<td>103</td>
</tr>
<tr>
<td>LSDLGVHAR</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>17</td>
<td>81</td>
</tr>
</tbody>
</table>
The sea distance had the second strongest effect, where low SD reduced the temperature on average by 0.13 °C in 2018 and 0.24 °C in 2021. High SD slightly increased the temperature in 0.1 °C in 2018 and in 0.12 °C in 2021. This indicates that the difference between land and sea temperature was large in 2021 and provided a cooled microenvironment closer to shore. The floor area ratio had the lowest influence on the indoor air temperature, where low floor area ratio decreased temperature in around −0.1 °C for both years and a high floor area ratio had near neutral (relative zero) effect. Overall due to the chosen heatwave periods during 2021 being more severe with longer and higher outdoor temperatures, the performance of all building groups was also lower than in 2018.

Table 4
The building group indoor air temperature mean decreasing effect of microenvironment factors in the whole summers of 2018 and 2021.

<table>
<thead>
<tr>
<th>Microenvironment factors combination</th>
<th>Temperature effect, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2018</td>
</tr>
<tr>
<td>Low sea distance</td>
<td>−0.13</td>
</tr>
<tr>
<td>SD = 0</td>
<td></td>
</tr>
<tr>
<td>High GVI</td>
<td>−0.37</td>
</tr>
<tr>
<td>GVI = 1</td>
<td></td>
</tr>
<tr>
<td>Low floor area ratio FAR = 0</td>
<td>−0.09</td>
</tr>
</tbody>
</table>

0.11 °C for 2021. The sea distance had the second strongest effect, where low SD reduced the temperature on average by 0.13 °C for 2018 and 0.24 °C for 2021. High SD slightly increased the temperature in 0.1 °C in 2018 and in 0.12 °C in 2021. This indicates that the difference between land and sea temperature was large in 2021 and provided a cooled microenvironment closer to shore. The floor area ratio had the lowest influence on the indoor air temperature, where low floor area ratio decreased temperature in around −0.1 °C for both years and a high floor area ratio had near neutral (relative zero) effect. Overall due to the chosen heatwave periods during 2021 being more severe with longer and higher outdoor temperatures, the performance of all building groups was also lower than in 2018.

The normalized (min-max normalization) temperature difference is shown to the relative performance of the factors, see Fig. 7 dashed line. In most cases, it followed the absolute temperature difference. However, it supported the rate of influence of factors, where the GVI and sea distance were dominant factors and floor area ratio had a lower influence, which was numerically mentioned above. On the other hand, the normalized difference showed, that during the 2018 and 2021 years, the building groups had similar patterns of performance. The main difference is that the long heatwave in 2018 was after short heatwave, so the building stock and environment was pre-heated. It resulted in lower temperature difference of the building stock as it shown in HSDHGVILFAR group.

3.4. The influence of microenvironment factors during different time periods

In both years, the relative performance of each group was consistent during the chosen time periods as shown in Fig. 8. Temperature differences between the building groups were more significant during short heatwaves than during long heatwaves. Early summer and late summer periods were closer to short heatwaves in terms of the relative temperature difference of the different building groups.

Fig. 8 shows the temperature distributions in groups during chosen periods via a bar chart where the cross is the average value from Fig. 9. Four time periods were presented and analyzed separately, representing the building stock performance of each group and their difference in specific weather and environmental conditions.

Overall, the temperature difference distributions of the groups were mostly under 0.5 °C, there were no visible or statistical patterns to notice, as shown in Fig. 8. The difference between short periods and long periods did not show a statistical difference and buildings in each group performed mostly alike. The average values were mostly around the middle of each bar, which means close to the normal distribution of values. The only measurable outliers were during late summer, when the average value was below the middle, meaning that some buildings were more reactive to the combination of cool building surroundings and solar insolation. Also, it should be noted, that temperature differences in 2021 were higher on average by 0.5 °C compared to 2018. It might be due to temperature profile differences: in 2021 average outdoor and indoor groups air temperature was higher, thus temperature difference was higher.

Fig. 9 represents the patterns of group performance during the chosen periods, shown as spider charts. Four time periods were presented.
Building and Environment 246 (2023) 110971

In the early summer high GVI reduced the temperature in the building groups during both years by around 0.8 °C for 2018 and 0.4 °C for 2021. The difference might be caused by higher insolation during the period in 2018. The low sea distance also decreased indoor temperature; in 2021 the effect was around 0.5 °C and in 2018 it was 0.19 °C. The difference might be due to the weather conditions before the studied period; in 2021, compared to 2018, the outdoor air temperature was lower. The low floor area ratio showed different performances in different years; the temperature reduced in 2018 and increased in 2021. The combination of floor area ratio and GVI had a limited effect on the indoor air temperature of the groups, which was also reflected in the influence of a combination of factors, where a combination of sea distance and GVI was predominant. The temperature difference between the best and worst performing groups was high due to the influence of building thermal mass; nights were still cool and thus the heat is able to dissipate.

During the first, short heatwave, which happens in the middle of the summer, the daily mean temperature was above 25 °C. The low sea distance reduced the indoor temperature in 2018 by 0.3 °C and the high GVI was even more 0.53 °C. In 2021, both factors had a similar temperature-decreasing effect of around 0.5 °C. The high floor area ratio gave a decreasing temperature of 0.14 °C. It is important to note, that combination of low sea distance and high GVI had the most influence. High GVI combined with a low floor area ratio had a less significant effect.

The performance during long heatwave showed that in both years daily mean temperatures in the buildings were above 27 °C. In 2018 there was a previous heatwave one day before the analyzed heatwave and the buildings had been already heated up, so the absolute temperature was higher (around 27.9 °C) than in 2021 with 27.2 °C. In 2018 the high GVI was the most temperature-reducing factor by 0.6 °C, thanks to the ability to mitigate insolation and cooling effect of evapotranspiration via outdoor temperature, and decreasing sea effect was only about 0.12 °C. In 2021 the sea effect was high, with a reducing temperature by 0.6 °C and a high GVI by 0.32 °C since the environment was

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Table 5
The building group indoor air temperature mean decreasing effect of microenvironment factors in 2018 and 2021.

<table>
<thead>
<tr>
<th>Microenvironment factors combination</th>
<th>Temperature effect, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Early summer</td>
</tr>
<tr>
<td>Low sea distance</td>
<td>-0.19</td>
</tr>
<tr>
<td>SD = 0</td>
<td>(-0.48)</td>
</tr>
<tr>
<td>High GVI</td>
<td>-0.79*</td>
</tr>
<tr>
<td>GVI = 1</td>
<td>(-0.36)</td>
</tr>
<tr>
<td>Low floor area ratio</td>
<td>-0.08</td>
</tr>
<tr>
<td>FAR = 0</td>
<td>(0.23)</td>
</tr>
<tr>
<td>Low sea distance: High GVI</td>
<td>-0.85</td>
</tr>
<tr>
<td>SD = 0: GVI = 1</td>
<td>(-0.64*)</td>
</tr>
<tr>
<td>Low sea distance: Low floor area ratio</td>
<td>-0.05</td>
</tr>
<tr>
<td>SD = 0: FAR = 0</td>
<td>(0.10)</td>
</tr>
<tr>
<td>High GVI: Low floor area ratio</td>
<td>-0.36*</td>
</tr>
<tr>
<td>GVI = 1: FAR = 0</td>
<td>(0.07)</td>
</tr>
</tbody>
</table>

*p-values were equal 0.06 or lower.

and analyzed separately, representing the influence of chosen urban microenvironment parameters during specific weather and environmental conditions.

In the early summer high GVI reduced the temperature in the building groups during both years by around 0.8 °C for 2018 and 0.4 °C for 2021. The difference might be caused by higher insolation during the period in 2018. The low sea distance also decreased indoor temperature;
not heated so much. The relative difference between groups was lowest among all time periods, as the mass of the building could not dissipate the heat during the night. The high floor area ratio showed a low ability to decrease the temperature in around 0.1 °C. The low floor area ratio contributed only with a combination of high GVI.

The group performance during the late summer was very similar to early summer, but the temperature difference between groups was the highest due to nights already being colder. The high floor area ratio decreased indoor air temperature by 0.2 °C. Low Sea distance had a reducing effect of about 0.5 °C, while other parameters and their combinations performed the same as in early summer.

The results show that urban parameters have a limited effect on indoor temperatures during the whole summer but they can have a more significant role during shorter time periods, such as short heatwaves.

3.5. The correlation of the local outdoor temperature with indoor air temperature

The room air temperature is affected by solar radiation through the window and by local outdoor temperature. It could be assumed that outdoor air temperature is the major factor that affects indoor temperate rise during long heat waves. To investigate how well local outdoor temperature correlated with indoor temperature, the room air temperatures in the clustered groups were compared with the local outdoor temperature simulated for 2018 and 2021 weather conditions in Helsinki. The outdoor temperatures of these areas were calculated by HARMONIE-AROME model and compared with each clustered groups’ summer mean outdoor temperatures. The results are presented in a way that makes it possible to see the correlation between outdoor temperature and building group indoor air temperature.

The p-values were <0.001 for each correlation between the building group and group’s area average temperature showing a very strong correlation. Overall, the correlation was acceptable and consistent: 0.3 and 0.4 for 2018 and 2021, respectively. Furthermore, the performance differences between the groups also correlated closely with probabilities of 0.5 and 0.6, respectively.

To investigate the correlation during a shorter period than the whole summer, the long heatwave period was chosen, as shown in Table 6. The correlation for the period for both years also showed p-values <0.01. This period reflected the building reaction to long exposure to high temperatures and the subsequent heating up of building stock. The weather during the periods was mostly the same with 2021 temperatures being slightly higher than in 2018, as seen in Fig. 10.

The outdoor local temperature of the periods was mostly the same in 2018 and 2021, but as mentioned earlier the short heatwave in 2018 had heated the buildings beforehand, which was reflected in lower correlation values, as shown in Table 6. The HSDH_GVIL_FAR building group showed consistently lower outdoor temperatures and this might explain why the overall absolute difference of indoor temperatures was higher compared to other groups. The same applies to the LSDL_GVIL_FAR group, where temperatures were also lower in about 0.5 °C. Indoor temperatures of other groups mostly followed outdoor temperatures. Overall, the correlation during the chosen period, where the influence of other factors was lower, was significantly higher at 0.6 on average.

4. Discussion

Climate change presents various challenges, including the overheating of apartment buildings during hot weather periods. For example, climate projections for Finland under the RCP forcing scenarios forecasts a considerable increase in temperatures in Finland, with winter temperatures projected to rise by 3–6 °C and summer temperatures by 2–4 °C by the end of the century [73]. In Norway, temperature
could rise by approximately 3–5 °C by the end of the 21st century [47]. The Nordic region has a building stock adapted to cold climates so buildings are well-insulated but mechanical cooling is rarely implemented. In addition, urbanization makes the building stock prone to overheating due to UHI.

In different climates, UHI is believed to be one of the main contributors to rising outdoor and indoor temperatures, which further increases the risk of overheating in urban areas. Heatwaves significantly contribute to the apartment overheating by rising the outdoor temperature and increasing insolation, direct and indirect, on the building stock. In the past, this challenge mostly occurred in urbanized areas in hot climates, and historically always had a significant effect on human life. In eastern China, UHI contributes to about 2.5 °C on average [74], in India up to 8 °C [75], and in the US from the 1.25 °C to 4.35 °C in cities compared to surrounding rural areas [76,77]. However, now and in the near future, regions, which have a cold climate, have started to encounter heatwaves more. Consequently, UHIs can increase the overheating in urban residences and lead to elevated health risks or in the case of mechanically cooled buildings, increased energy consumption.

The main sources of heat gains are predominantly solar radiation and internal gains from appliances. Solar radiation often emerges as the largest contributor to heat gains in buildings, contributing up to 50% of the cooling load during the summer months [78]. Internal heat gains originate from appliances, lighting, and human occupancy, making up a significant proportion of about 15% of heat gains [79]. Heat transmission through building components such as walls, roofs, and windows can increase heat gains by up to 20–30%, especially during the summer months [20]. To mitigate this influence, we might address albedo or the reflective quality of surfaces where light-colored or reflective materials, which have high albedo, can reduce heat absorption. For instance, white roofs can reduce annual cooling demand by 10–15% in Mediterranean climates [80]. High-performance glazing and shading systems can effectively reduce solar heat gains by up to 75% [81]. Improved appliance efficiency and behavioural modifications can potentially curb these internal heat gains by up to 30%. However, not all of these approaches work in the Nordic climate.

The main challenge in Nordic conditions is that buildings should keep heat during winter and dissipate it during hot weather. For instance, the reflective or white coating will dissipate heat during winters and summers, which does not contribute to the reduction of heating demand. Internal gains are well-addressed due to high energy-saving goals. In summary, a combination of high-performance glazing, effective building shading, and strategic use of night cooling can significantly aid in preventing overheating in Nordic climate conditions. However, these are measures on the building level, and on the district level challenges might be addressed with wise city design, greenery, and water sources. In this case, urban microenvironment parameters start to play a significant role.

The study shows that greenery had a consistent effect during all time periods regardless of seasonal bias in Nordic conditions, addressing challenges of short and long heatwaves. The relatively low PAR in Helsinki allows for combining greenery evapotranspiration with shading from insolation due to the low overall residential building height. The utilization of sea distance is more limited due to the city design, however also might be empathizing to settle new buildings in coastal areas, which will increase the ability to withstand short heatwaves. In general, the wise implementation of urban microenvironment parameters analysis in building and city design planning will increase the sustainability of cities and lower overheating risks. Furthermore, wise microenvironment (urban) design might be a step in building resilience as a part of making them less vulnerable to short or long-term disruptions, heat waves in this case [82]. On the next level of cooling system implementation cooling microenvironment effect also might help mitigating indoor overheating as might be able to increase the depth of control, as it might occur due to high level of fluctuation of outdoors parameters [25]. Also, monitoring and predicting city environment behaviour via data-driven or physically-based models will benefit significantly, which might be developed further by advancing study analysis of the effect of urban microenvironment parameters in dynamic (year-a-year).

In comparison to other studies, the results of this study show the maximum cooling effect of urban microenvironment factors in the Helsinki region to be about 1.2 °C with the average being about 0.7 °C. In Copenhagen, additional urban greenery lowered the temperature by 0.7 °C. In Greece [45], however, due to a hotter climate, the results were higher: 1.5 °C from greenery and 3.0 °C from water sources such as pools and fountains. As mentioned above, the UHI effect on overheating was around 1.5–2 °C in warmer climates, thus the ability to mitigate about 1 °C was important. In the future wise analysis of urban microenvironment factors in city design might become one of the leading approaches to lower indoor temperatures indoor.

4.1. Study limitations

At the moment, our study had several limitations to address: sensor placing, data averaging bias, presented by our building type and chosen urban microenvironment parameters. The sensors in apartments were placed with no exposure to direct sunlight, however only one sensor was presented in one, two or more room apartments, thus the data was not averaged by rooms. However, the sensors were consistently placed in the main corridors of the apartments, which interconnected all the rooms, regardless of their orientation, thus insolation exposure. In addition, we had at least several (about 1–2 each) apartment types in each studied building, thus averaging the resulting building performance, presented by averaged apartment temperatures. On the other hand, most of our buildings were presented with social housing, not including other types of residential building stock. Also, we were limited in addressing each apartment as an entity due to personal data usage limitations, thus the averaging of similar apartments was introduced. Although we believe, that in Finland residential building stock of any type meets the energy and IAQ requirements, thus, the presented bias should be limited. For the correlation, the greenery is represented by GVI, as it was measured for the Helsinki region with a sufficient amount of data and present greenery, and the overall shading of the streets. The GVI does not directly address the greenery height or their reflection on the building envelope during the day however indicatively shows the overall greenery level, which might be then addressed by introducing additional data about plant heights and others. In addition, we know that the urbanization of Helsinki area is comparably low, thus average building height is around 5 floors.

It is also worth noting that for analysis the average temperatures were used due to described previous attempt to lower the effect of measurement errors and building stock differences and to represent the average influence of urban microenvironment factors. Although momentary the effect might be different during daily peaks of insolation or nighttime periods of tropical weather. We might estimate that during daily peaks the temperature-decreasing effect of factors might be even higher, helping mitigate the overheating and affect thermal comfort. On the other hand, the air temperature in individual rooms in apartments or even apartments facing south might be on a higher level, thus locally buildings significantly differ from average building performance.

4.2. Further research

Building performance is influenced by various weather conditions and occupant behavior. Maintenance or operational failures can also introduce uncertainties. As a result, these variables can significantly affect system performance, indoor climate, and energy efficiency. Fortunately, modern buildings and their ventilation systems can now provide more information about their performance through installed sensors at both the apartment and ventilation system levels. The data might be collected by buildings owners, and then used for control and analysis. Furthermore, the analysis results can be shared with building
designers to optimize building projects. Therefore, the primary focus of further research should be on the ability to conduct annual data analyses of building stock performance to predict performance in the following years. This analysis should initially consider the potential effects of changing outdoor conditions or occupant behavior based on past data. This can be accomplished by integrating building simulation analysis with building stock indoor air temperature measurements and creating operational digital twins on the building level. These digital twins could also consider urban microenvironmental factors and different weather models in large-scale city-level simulations. These models will enable the design of more sustainable districts with known performance, addressing future climate changes while incorporating them into urban design, including microenvironmental factors like green spaces and water sources, such as lakes or seas.

5. Conclusion

This research assessed the impact of urban microenvironment parameters on indoor air temperature in Nordic conditions. The analysis utilized the measured room air temperature of approximately 400 apartment buildings in Helsinki, collected in the exceptionally warm summers of 2018 and 2021. The urban microenvironment parameters were green view index (GVI), floor area ratio and distance of buildings from the sea. Buildings were clustered into eight groups representing levels of urban parameters selected. The 4 time periods in each summer were chosen to assess the seasonal variation of vegetation, ISA and environment temperature conditions. The results were also correlated with the latest Finnish meteorological institute city and weather prediction model, based on HARMONIE-AROME, to understand the deviation in outdoor and building groups indoor temperatures.

The results of clustered building groups indoor air temperatures and their differences between groups showed a strong correlation with chosen parameters with p-values <.01. The most substantial influence of the urban microenvironment was observed during short heatwaves in the middle and late summer. The best-performing group had indoor temperature lower than others on average by 0.4°C and compared to the warmest group by 1.2°C. The low sea distance reduce the indoor temperature in 2018 by 0.3°C and the high GVI even more by 0.53°C. In 2021, both factors had a similar temperature-decreasing effect of around 0.5°C. The influence of urban microenvironment factors during the long midsummer heatwave was lower, but GVI showed the most temperature-reducing influence. In 2018 the high GVI was the most temperature-reducing factor by 0.6°C and decreasing sea effect was only about 0.12°C. In 2021 the sea effect was high, reducing the temperature by 0.6°C and high GVI by 0.32°C. Building groups with higher GVI demonstrated a greater ability to endure heatwaves. Analysis revealed that long heatwaves significantly reduced the influence of urban microenvironment parameters and necessitated alternative approaches for passive or active cooling.

The correlation of indoor air temperatures of the clustered building groups, their differences between groups, and outdoor temperatures of the areas of the groups was also strong with p-values <.001 during chosen periods. The closest correlation was with groups with high sea distance and low floor area ratio, 0.4. The groups with low sea distance showed a lower correlation of around 0.3. During the long heatwave, in both years correlation was higher at up to 0.5, however with the same pattern, where sea distance and floor area ratio affected the results the most.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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I. Kravchenko et al.