Urban microclimate impact on ventilation and thermal performance of multi-family residential buildings: two case studies in different climates and urban settings

Agnese Salvati[1] and Maria Kolokotroni[*2],

1 Barcelona School of Architecture ETSAB - UPC
Diagonal, 649
08028 Barcelona, Spain

2 Brunel University London
Kingston Lane, Uxbridge, UK
**Corresponding author:*
maria.kolokotroni@brunel.ac.uk

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ABSTRACT

Urban settings change the microclimate around buildings and resulting thermal comfort inside. This paper presents a method to consider microclimatic conditions, especially the effect of wind variations around the building, which impacts natural ventilation rates and indoor operative temperatures. Air and surface temperature and wind speeds were studied using ENVImet for two areas located in Cadiz (Spain) and London (United Kingdom), representing temperate and hot European climates and moderate and dense urban settings. The outputs of these microclimate simulations provided the spatial and temporal distribution of wind speed and directions at the building facades of two multi-family residential buildings located in the middle of the simulated areas (one in London and one in Cadiz) and the surface temperatures of surrounding buildings. These were used as boundary conditions to the EnergyPlus models of the two buildings to investigate their impact on achievable natural ventilation rates and the indoor thermal environment. Data for the case-studies were available through the ReCO2ST project. The ENVImet hourly wind speed values were used as input to the Air Flow Network models of EnergyPlus for the calculation of the wind pressure and the ventilation rates of the two buildings. The hourly surface temperatures calculated by ENVImet were assigned to the shading surface in front of the main façade of the case-study building located in Cadiz, to investigate its impact on thermal radiation emission and indoor operative temperatures. This was done by using the "Surrounding surface" objects of EnergyPlus V9.3.0. It was found that ventilation rates are reduced (in comparison to meteorological weather files) and this reduction impacts negatively on internal operative temperatures. The surface temperature of the facing building has a further negative impact during daytime, increasing the maximum indoor operative temperature. A thermal comfort analysis was carried out indicating that the selection of a suitable weather file and microclimatic conditions is essential for more accurate predictions of internal thermal comfort and will assist in the sizing of passive and active systems to avoid overheating.

KEYWORDS

Microclimate, urban, weather files, ventilation, thermal comfort

1 INTRODUCTION

In thermal simulations studies of buildings, ambient conditions are accounted for by using weather files of the building's location, providing hourly values of typical ambient conditions: temperature, humidity, solar radiation, wind. Weather files are built using historical observational data usually over 30 years; they are based on measurements at meteorological stations usually at airports. Therefore, weather files do not account for characteristics of the urban environment which modifies climatic conditions, especially those of air temperature and wind. In addition, buildings designed and built today, will last for many years. Therefore, future climate projections should be used to predict how our buildings will perform in 30 or 50 years. Using such climate projections can ensure that energy and comfort performance simulations can more realistically predict future performance – avoiding what has been termed ‘performance gap’, between measured performance and predicted performance.

The impact of the overlapping effect of global warming and urban microclimate on building thermal performance is therefore important for our understanding on how building will perform now and in the future. Methodologies for generation of future weather files for building simulation exist following IPCC scenarios (Herrera et al. 2017; IPCC 2000, 2014). Methodologies which include both future weather and urban microclimate are less developed. Extensive research has been carried out on urban climate models and coupling methodologies to include urban microclimate in dynamic thermal simulation (DTS) (Afshari 2017; Jain et al. 2020; Lauzet et al. 2019; Mao et al. 2017; Tsoka et al. 2018; Yang et al. 2012). However, very few attempts have been reported to generate future weather data that also include urban effects, to investigate the thermal performance and overheating risk of buildings under future urban climate conditions (CIBSE 2014; Kolokotroni et al. 2012; Mauree et al. 2018). To fill this gap, we proposed a methodology based on the use of urban climate models (UWG), empirical wind models (URBVENT) and detailed microclimate models (ENVImet) for urban microclimate simulation, in order to investigate the overlapping effects of climate change and urban effects on the future performance of urban buildings.

2 GENERATING FUTURE URBAN MICROCLIMATE CONDITIONS

The methodology adopted in this study to generate future urban microclimate conditions to perform DTS is reported in Figure 1.

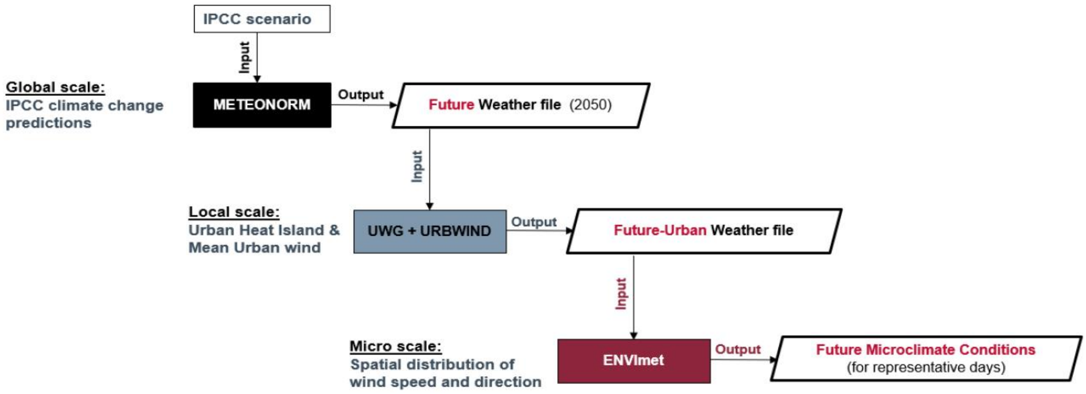

Figure 1 Method to generate future urban microclimate conditions to perform dynamic thermal simulations

METENORM was used to generate future weather files based on the IPCC emission scenarios. The future weather files were used as input to the UWG (Bueno et al, 2013) and URBVENT (Ghiaus and Roulet, 2004) models to generate future-urban weather files, capturing the local modifications of air temperature and wind speed determined by an urban area at the local scale (Salvati et al. 2019, 2020). These simplified models do not account for the impact of the actual three-dimensional geometry of the building and its surrounding obstacles on the air flow around the building. However, important microclimate phenomena are also driven by the shape and arrangement of the buildings and other urban elements and their interaction with wind flow and solar radiation. These micro-scale phenomena have significant impact on the outdoor thermal comfort but also on the building energy performance in urban context (Futcher, Kershaw, and Mills 2013; Futcher, Mills, and Emmanuel 2018; Nazarian et al. 2019; Nazarian and Kleissl 2015; Salvati and Kolokotroni 2019, 2020).

The novel contribution of this paper consists in using the future-urban weather file as input to ENVImet simulations, to investigate the impact of the buildings’ shape and urban context on the air flow and surface temperatures and if these microclimate modifications have negative impacts on the indoor environment.

ENVImet is a microclimate simulator for urban areas with high spatial and temporal resolution. The model has been further developed in the last years (Huttner and Bruse 2009). The last release V4.4.4 allows to run simulations in "full forcing" mode, namely using local hourly values of air temperature, relative humidity, wind speed and direction as input inflow boundary conditions to the three-dimensional CFD atmospheric model, increasing significantly the model accuracy (Salvati and Kolokotroni 2019).

The ENVImet simulations were performed for two case-studies, using as input the air temperature, relative humidity, wind speed and direction of the hottest week of the future weather files generated by METENORM and the urban wind speed attenuation based on the URBVENT models. The two buildings are located in London (UK) and Cadiz (South Spain) and were selected as case-studies because data were available through the ReCO2ST project (ReCO2ST, 2022). The ENVImet models for Cadiz and London are reported in Figure 2.

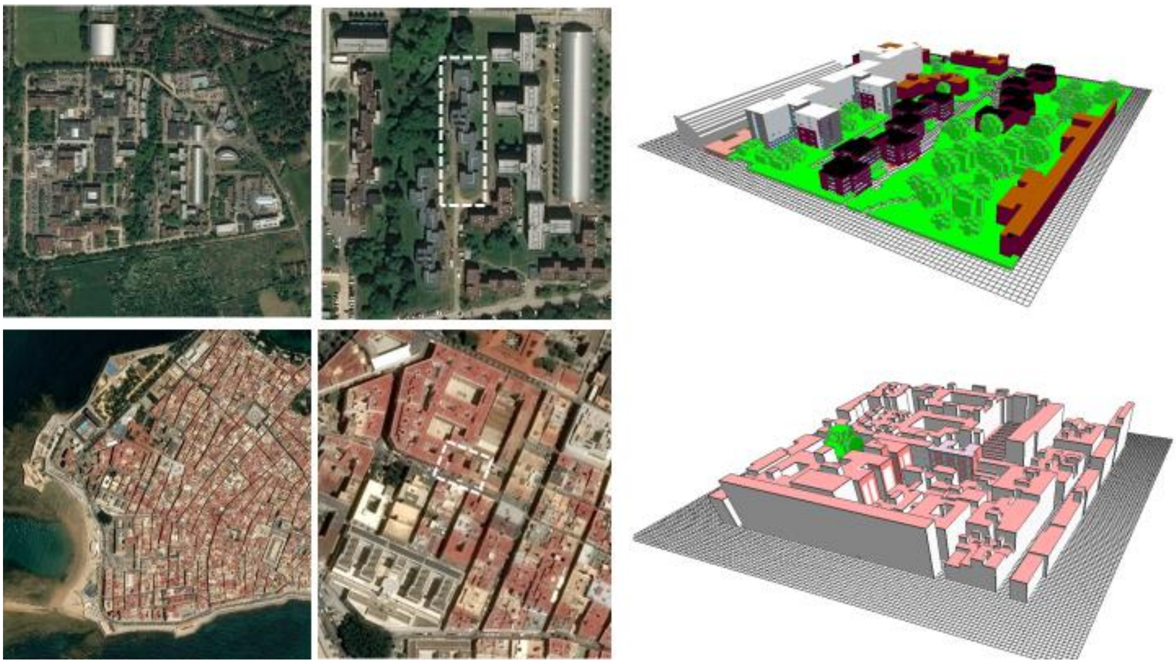

Figure 2: Aerial view of the London and Cadiz buildings and urban context and corresponding ENVImet models

The outputs of the microclimate simulations provided the spatial and temporal distribution of wind speed and directions at the building facades and the surface temperatures of surrounding buildings. These were used as boundary conditions to the EnergyPlus models of the two buildings, to investigate their impact on the indoor thermal environment. The ENVImet simulations were run for 108 hours so as to have hourly outputs for 4 days, discarding the first 12 hours buffer time.

3 LINKAGE BETWEEN ENVIMET OUTPUTS AND ENERGYPLUS

The outputs of the ENVImet microclimate simulations were used as input values to the Air Flow Network (AFN) models in EnergyPlus for the calculation of the wind pressure and the ventilation rates of the two buildings. This entailed a different approach compared to the standard approach using pressure coefficients.

The EnergyPlus AFN model calculation of the wind pressure (p_w) at each opening is based on Bernoulli's equation (1)

$$p_w = c_p \rho \frac{V_{ref}^2}{2} < \infty \qquad (1)$$

Where c_p are the wind pressure coefficients and V_{ref}^2 is the local wind speed at the building height calculated with the power law profile, considering the roughness of the weather station site and the building site and the height above ground level (U.S. Department of Energy 2019). In this study, the pressure coefficients values for each façade have been set based on the AIVC TN44 tables for low-rise buildings surrounded by obstructions equal to the height of the building (Orme, Liddament, and Wilson 1998). The main weakness of this procedure consists in the calculation of the local wind speed based on the power law profile, which is not valid within the urban canopy layer where the presence of large obstacles (buildings, trees) significantly modifies the airflow around buildings. The inaccuracy of the ventilation potential due to this approximation can be relevant, since the wind speed elevated to the second power is the major determinant of the wind pressure calculation.

In this study, the standard approach using the undisturbed wind speed and the pressure coefficients is compared to another approach using the hourly values of wind speed and direction at each facade derived from ENVImet simulations. The “Outdoor:nodes” objects in EnergyPlus were used to set the hourly wind speed and direction values calculated by ENVImet as input values to the external nodes of the AFN model for the calculation of the wind pressure. Using this approach, the wind pressure at each AFN external node is calculated as follows:

$$p_w = \pm \rho \frac{V_{CFD}^2}{2} \qquad (2)$$

Where V_{CFD}^2 is the hourly wind speed in front of the building façade calculated by ENVImet and $\pm$ is the direction of the pressure determined by the relative angle of the wind stream on the facade, considering a positive pressure (inward acting) on the windward facades and a negative one (outward acting) on the leeward surfaces.

In the case of Cadiz, additionally the impact of the surface temperature of the wall opposite to the studied building was investigated. The building in Cadiz is located in a narrow canyon, facing another building of similar height. Some studies highlighted that the actual temperature of surrounding urban elements may affect the thermal performance of urban buildings, by decreasing the heat losses though long-wave exchange with the environment (Jain et al. 2020; Palme and Salvati 2018; Salvati et al. 2020). For this reason, the impact of the actual temperature of the wall facing the studied building was also investigated. To do so, the hourly surface temperatures calculated by ENVImet have been assigned to the shading surface in front of the main façade of the Cadiz building. This was done by using the new “Surrounding surface” objects of EnergyPlus V9.3.0 and assigning the corresponding view factors to the external surfaces of the main façade of the building. A conceptual illustration of the link between the ENVImet outputs and the EnergyPlus models is reported in Figure 5 and Figure 10.

4 MICROCLIMATE ANALYSIS: WIND SPEED AND DIRECTION AT THE DEMO BUILDING SITES

The microclimate simulations confirmed the relevant role played by the 3D urban morphology on wind speed and direction around the studied buildings. The results for the dominant wind directions are reported in Figure 3 and Figure 4 for London and Cadiz, respectively. In the case of London, the wind speed at the building facades is affected by the surrounding buildings and trees and by the shape of the building itself. In Cadiz, the wind flow in the main street is significantly reduced by the dense urban fabric and its orientation with respect to the dominant wind direction (South-West), despite the proximity to the sea. The simulations also showed that the wind speed in the courtyard is very low for any wind speed and direction.

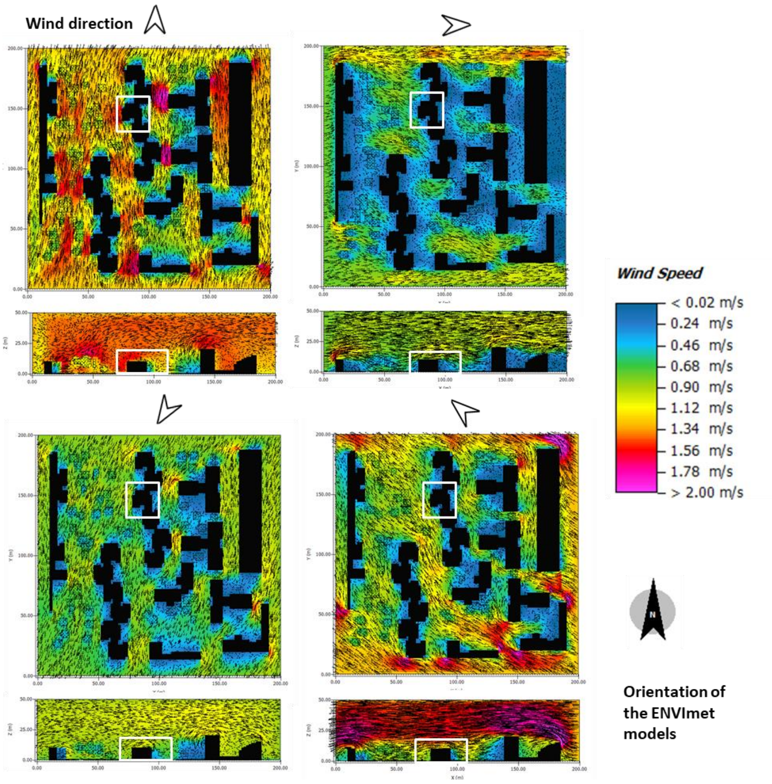

Figure 3: ENVImet results of the airflow around the building in London for different dominant wind directions. The horizontal maps represent the wind speed distribution at 4.5m above ground level, corresponding to the height of the studied floor. Below each horizontal map, the vertical distribution of wind speed is reported

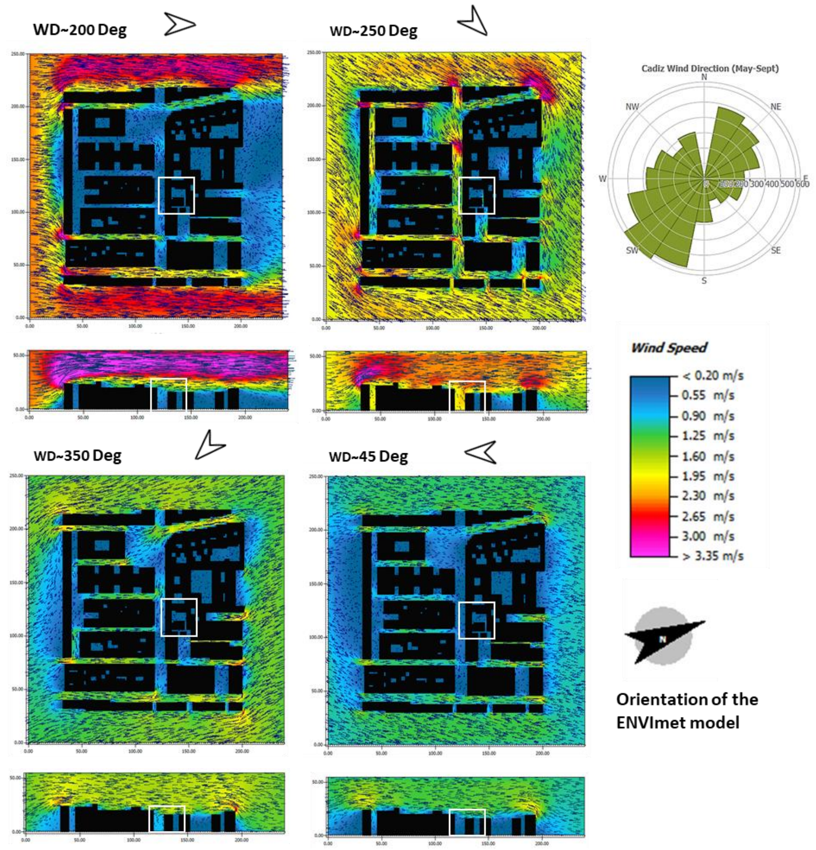

Figure 4: ENVImet results of the airflow around the building in Cadiz for different dominant wind directions. The wind rose for Cadiz is reported in upper-right corner. The horizontal maps represent the wind speed distribution at 4.5m above ground level, corresponding to the height of the studied floor. Below each horizontal map, the vertical distribution of wind speed around the building is reported.

5 IMPACT OF MICROCLIMATE CONDITIONS ON INDOOR THERMAL COMFORT

The simulation results showed that the site-specific wind speed and surface temperatures have a clear impact on the indoor thermal operative temperatures and air change per hour of the two buildings. The wind speed at the different openings of the Cadiz model as calculated by ENVImet and by EnergyPlus are compared in Figure 6. The same figure also shows a clear difference between the air temperature and the opposite wall temperature especially during daytime and also during nighttime in the hottest day.

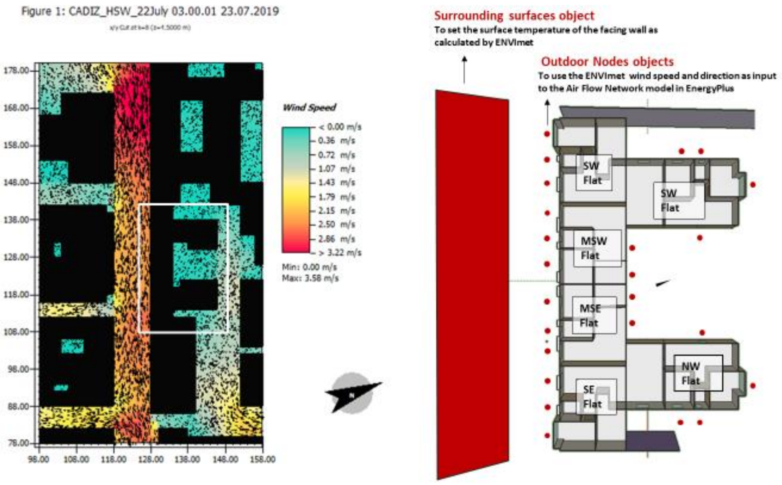

Figure 5: ENVImet outputs and use of outdoor nodes and Surrounding Surface objects in the Cadiz model

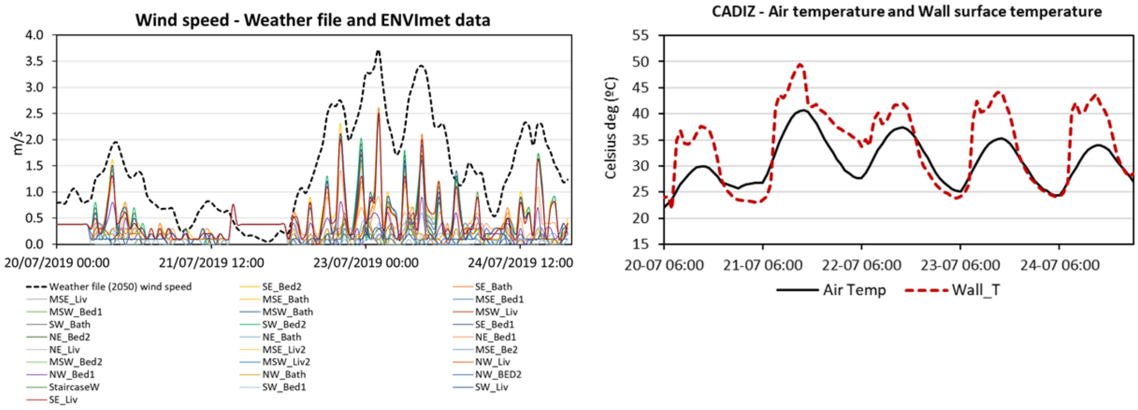

Figure 6: Difference between the weather file and the ENVImet wind speed data at the height of the windows in the Cadiz model (left) and difference between the air temperature and the surface temperature of the wall opposite to the studied building (right).

Figure 7 shows a comparison of the rooms' air change per hour (ACH) as calculated using the standard approach and the weather file data or the ENVImet data. The second graph illustrates the impact of the modified ACHs on the room operative temperatures. The results confirm that the decrease wind speed in urban canyons has an impact on the natural ventilation potential of urban buildings, decreasing the ventilation rates. This is more or less evident depending on the room location and opening characteristics. The biggest reduction is found for the rooms having larger windows and for the rooms of the flats MSW and MSE, located in the middle of the main façade of the building.

The reduced ventilation rates have an impact on the indoor operative temperatures, with an average increase of 0.2 – 0.8 ºC across all the rooms and a maximum increase of up to 2.8ºC due to reduced ventilation rates.

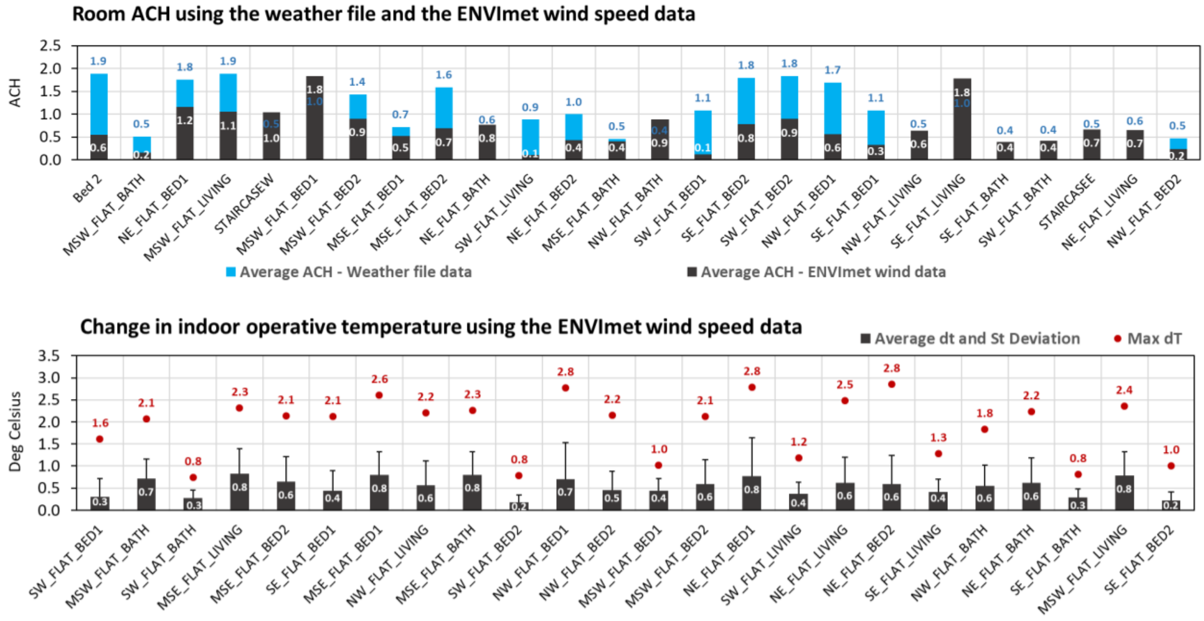

Figure 7: Top: Comparison of the room ACH calculated using the weather file and ENVImet wind data for the Cadiz building. Bottom: Average and maximum impact of reduced ACH on the room operative temperatures.

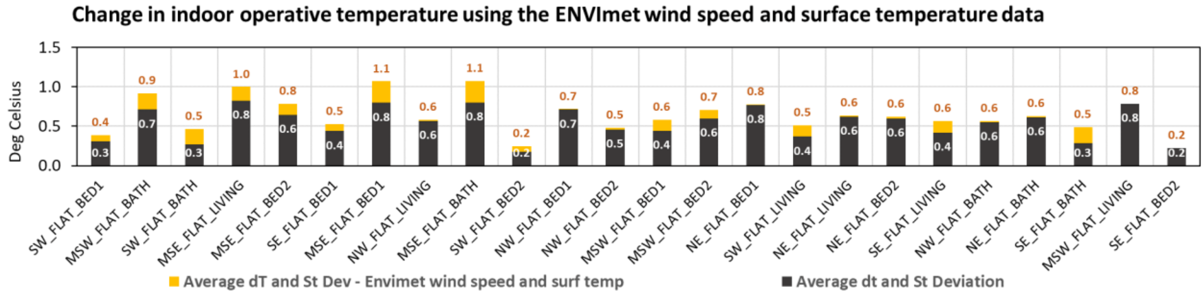

Figure 8: Increase of the indoor operative temperatures due to the reduced wind speed (grey bars) and surrounding surface temperatures (yellow bars) for the Cadiz demo buildings

A further increase in the indoor operative temperatures of the room facing on the main street is determined by the actual surface temperature of the opposite building, as shown in Figure 8. The hourly values of wind speed, outdoor temperature and indoor operative temperature have been reported in detail for one of the rooms of the building in **Error! Reference source not found.**.

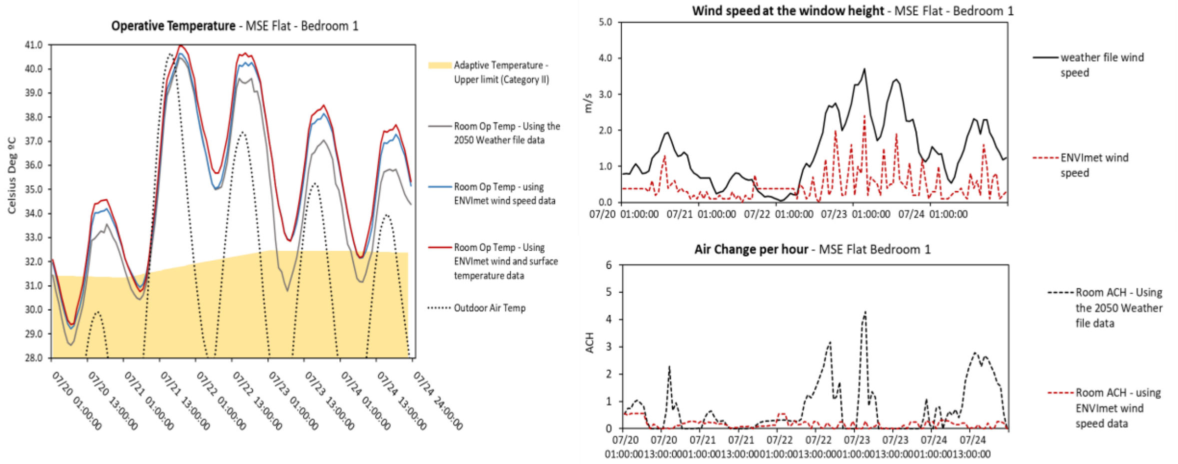

Figure 9: Hourly values of wind speed, outdoor temperature and indoor operative temperature under the different boundary conditions for the Bedroom 1 of the flat MSW in the Cadiz demo building.

These graphs show that the increase of the indoor operative temperature due to the attenuation of wind speed in the urban fabric is more evident on the days with stronger winds (23rd and 24th of July) and it has an impact on both the daytime and the nigh time indoor temperature. Instead, the surface temperature of the facing building has an impact during daytime, increasing the maximum indoor operative temperature.

The modification of wind speed and direction due to the shape of the building and the surrounding obstacles has an impact on the ventilation rates and indoor operative temperatures of the demo building in London. Figure 11 shows that the wind speed at the building facades is much lower than the estimation done by EnergyPlus using the power law profile.

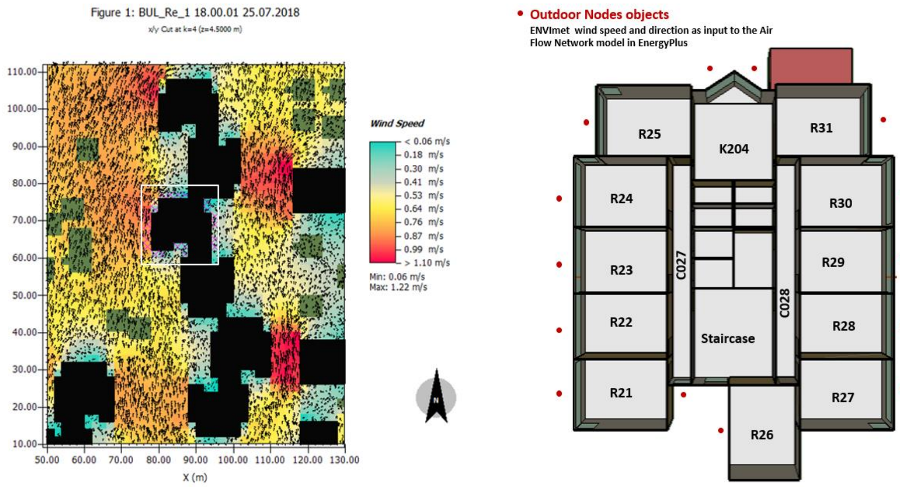

Figure 10: ENVImet outputs and use of outdoor nodes in the London demo building EnergyPlus model

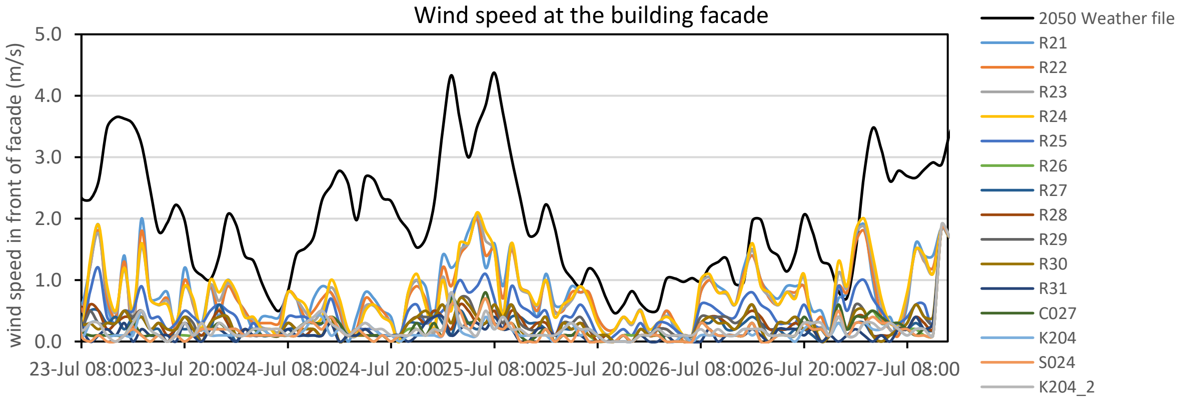

Figure 11: Difference between the weather file and the ENVImet wind speed data at the height of the windows in the London demo building.

The reduced wind speed has a clear impact on the ventilation rates of the bedrooms, in particular those on the East facade (R21, R22, R23 and R24), as shown in Figure 12. Using the ENVImet wind data instead of the weather file data, the ACH of these rooms is reduced by about 35%, from an average of 3.1 to an average of 2 ACH. The other rooms are much less affected by reduced wind speed. In some cases, the ventilation rates increase using the ENVImet data instead of the pressure coefficients and weather files data. This happens for the bedroom R25, which is located on the corner, it is probably due to the beneficial effect of a different wind speed and wind pressure on its window compared to the other windows on the same façade, contributing to create a pressure difference with the other spaces. The reduced ventilation rates of the east-façade rooms also have a significant impact on the indoor operative temperatures of the rooms, which increase of 1.0-1.1 ºC on average (Figure 12). The maximum increase of the operative temperature due to the reduced ventilation reaches up to 3.7 ºC.

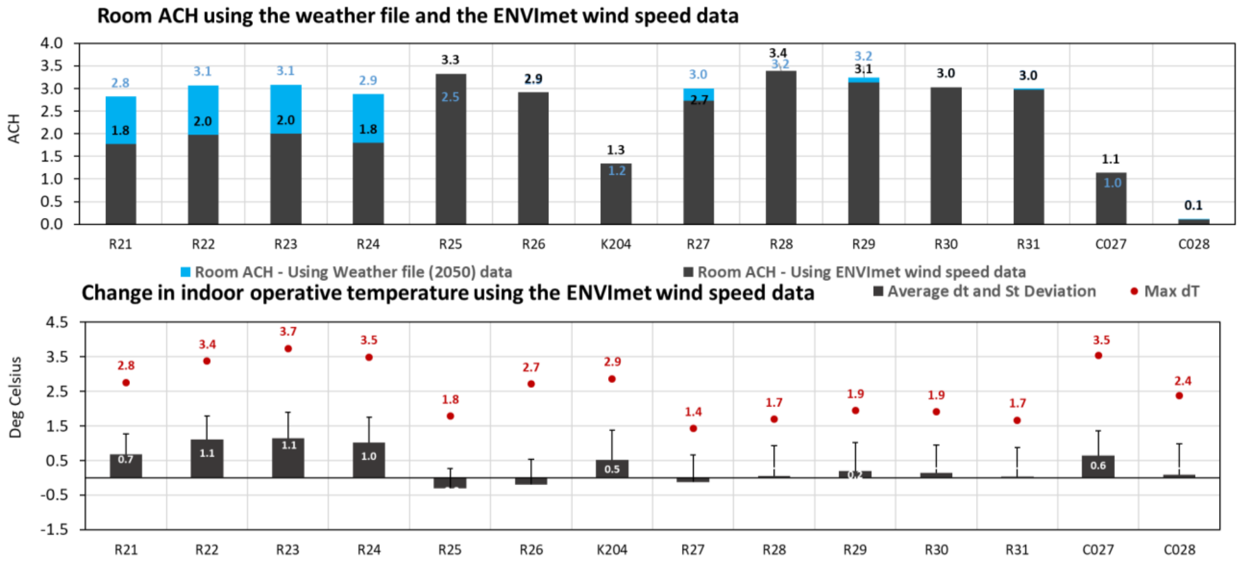

Figure 12: Top: Comparison of the rooms ACH calculated using the weather file and the ENVImet wind data for the London demo building. Bottom: Average and maximum impact of reduced ACH on the room operative temperatures

6 CONCLUSIONS

A method was developed to consider microclimatic conditions, especially the effect of wind variations around the building in urban context, which impacts natural ventilation rates. Air and surface temperature and wind speeds were simulated using ENVImet and the resulting microclimatic conditions were used as inputs to EneryPlus simulations by setting hourly values of wind speed and surface temperatures to the AFN model outdoor nodes and the “surrounding surface” objects of EnergyPlus. It was found that ventilation rates are significantly reduced in comparison to a standard approach using the meteorological weather files data and this reduction impacts negatively on internal operative temperatures in summer. A thermal comfort analysis was carried out indicating that the selection of a suitable weather file and microclimatic conditions is essential for more accurate predictions of internal thermal comfort and will assist in the sizing of passive and active systems to avoid overheating.

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