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Urban Microclimate and Energy Performance:
An Integrated Simulation Method

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ABSTRACT: In the design practice simulation methods are already widely used to support the understanding of energy performance and to help designers in reducing energy demand during the design process. However, energy simulation tools are largely limited to the individual building level, and urban microclimate conditions and variations in local wind, solar radiation, and air temperature patterns in which buildings express their energy performance are largely overlooked. In order to include microclimatic data in the computation of space cooling and heating consumption and enlarge the scale of analysis from single buildings to district scale, a new simulation method has been developed. The proposed coupling procedure links the microclimate software ENVI-met and the City Energy Analyst energy simulation tool and it is employed in the energy assessment of a urban re-development project in the city of Zurich, Switzerland. The results show that, considering microclimatic boundary conditions, the average hourly energy loads vary for daytime and night-time peaks and moreover a variation can be noticed in terms of total space heating and cooling consumption on the hottest and coldest day of a typical year.
KEYWORDS: Energy demand, microclimate, integrated simulation, ENVI-met, CEA.

1. INTRODUCTION

In proceeding through 'the Grand Transition', the world energy consumption is predicted to increase by 2060 in all the three main scenarios explored by the Word Energy Council [1]. Although new technologies and energy policies will moderate the final energy demand, this is expected to grow between 22% and 46% by 2060 due the global demographic growth.

In European countries, where demographic growth is concentrated in urban areas, urban transformation practices have seen a shift from an expansive development model to a compact and concentrated one, which has implied redevelopment projects in inner city areas. In this phenomenon of 'Urban re-densification' one of the main challenges is to understand and control the effects of the designed urban form on the urban microclimate during the design process, which doubly influences the physical well-being of people in the outdoor space and the energy performance of buildings.

Although in the design practice simulation methods are already widely used to support the understanding of energy performance and to help designers reduce energy demand during the design process, energy simulation tools are largely limited to the individual building level. Furthermore, urban microclimate conditions and variations in wind, solar radiation, and air temperature patterns are largely overlooked, as overall climate data are used. The reasons can be found on the restriction of modelling tools for microclimate simulations and on the difficulties in modelling large urban areas.

Therefore, in this paper a method is presented for the integration of urban microclimate and building energy simulations, and it is applied to evaluate the energy performance of a new masterplan for the 'Hochschulquartier' in central Zurich, Switzerland.

In Section 2 we present the coupling approach by describing the simulation tools ENVI-met and City Energy Analyst (CEA), and the linking method.

Section 3 presents the case study employed for the testing of the method and the specific setting to perform the analysis. Finally, in Section 4 and 5 the results are presented and discussed.

2. METHODOLOGY

2.1 Simulation tools

In order to understand the impact of urban microclimate on the energy performance two software tools have been used in this study:

- ENVI-met [2], an urban microclimate model for outdoor environmental prediction based on spatial configuration;
- City Energy Analyst (CEA) [3], an urban simulation engine for the assessment of district energy systems.

ENVI-met is a three-dimensional prognostic microclimate model designed to simulate the interaction between surfaces, plants and air in an urban environment [2]. It is widely used to estimate and assess outdoor thermal comfort [4, 5, 6] and the impact of the urban microclimate on building energy use [7, 8]. The atmospheric model computes mean air flow, turbulence, fluxes of direct, diffuse and reflected short-wave and long-wave radiation, and air temperature and humidity.

Two groups of inputs are necessary for the computations. A first group of spatial information, such as topography, building geometry and façade/surface materials, is used for the construction of the spatial model. A second group is constituted by meteorological input data such as initial air temperature, humidity and wind speed at 10m height. ENVI-met Version 4.0 Science as used in this study furthermore gives a simple forcing option that allows hourly forcing of air temperature and relative humidity.

The City Energy Analyst (CEA) is a computational framework for the analysis and optimization of energy systems in neighbourhoods and city districts. It consists of a collection of tools for the analysis of urban energy systems [9] based on comprehensive mathematical models using the latest ISO and SIA standards and the state-of-the-art in research. The tool allows users to analyse the energy use, carbon emissions and financial benefits of multiple district-scale design scenarios in conjunction with optimal schemes of distributed generation. In order to run a CEA simulation, two general groups of inputs are necessary. The first are primary inputs to the CEA modelling framework and consist of weather data, spatial information (topography and geometry of the buildings in the zone of study and in the surrounding area) as well as general characteristics of the buildings in the area of analysis (construction year, renovation dates and functional program of the building). The secondary inputs correspond to additional inputs that are necessary to run simulations but which may be assumed by CEA based on the primary inputs by looking into a database of typical building properties. These include architectural properties (such as building materials, conditioned floor area and window-to-wall ratios), the energy systems used in the buildings (both for supply and distribution throughout the building of heating, cooling and electricity), indoor comfort properties (set point and set back temperatures and ventilation rates), and internal loads (water and electricity demands for various services, and sensible and humidity gains due to occupant presence). Finally, other input information such as system controls and schedules for occupancy, electricity and hot water are selected by default from the CEA database but may again be edited by the user based on a given project's needs.

2.2 Coupling method and procedure

The method to use ENVI-met outputs as boundary conditions for CEA energy simulation consists of three main phases (Fig.1). In the first phase, the spatial model for the selected case study is built in ENVI-met (4.0) and simulations are performed using the simple forcing method by using weather data for the selected days. Secondly, output data for air temperature, wind speed and relative humidity are exported and aggregated in a 3D buffer around single buildings in a GIS platform (ArcGIS, Esri). In the third phase, the aggregated data are imported in the CEA software and used as boundary climatic conditions for the calculation of the energy demand for each building in the simulation domain.

The outdoor temperature is used in calculating the thermal loads in the building, which in CEA is done through a resistance-capacitance model based on the methodology described in ISO 13790 [10]. The detailed calculation methods are discussed in Fonseca & Schlueter [9]. The relative humidity, on the other hand, is mainly used in the latent load calculations, which are

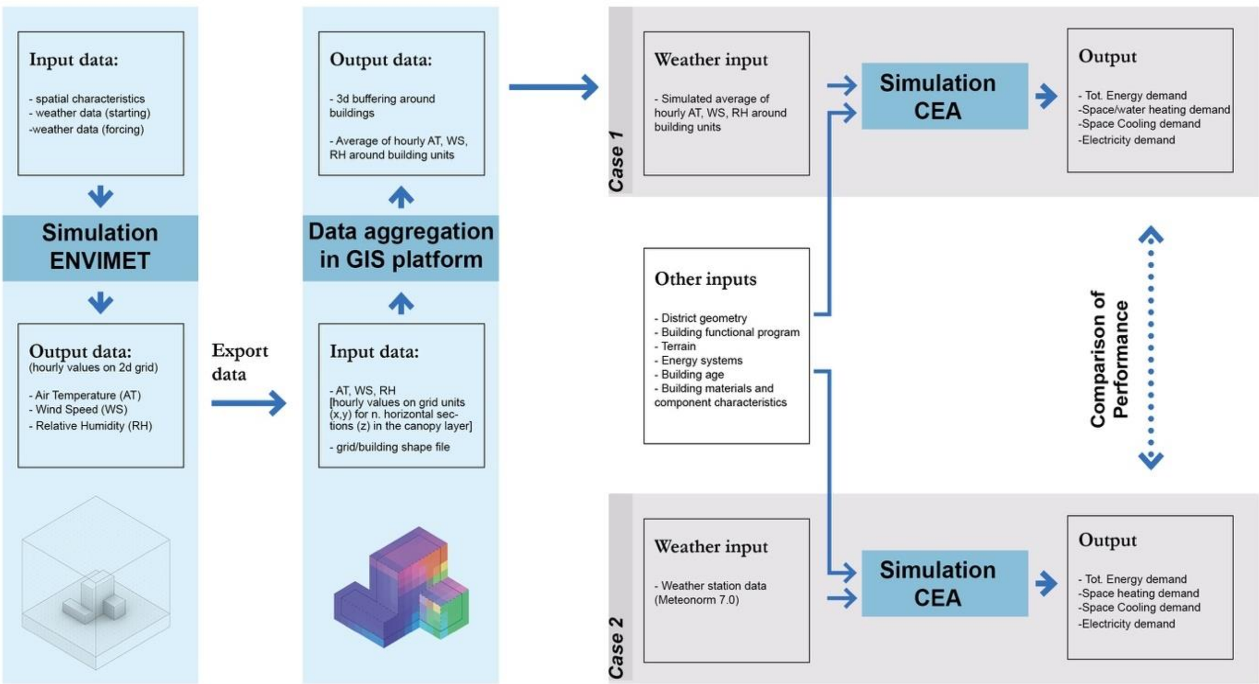

Figure 1: Methodological scheme

based on ISO standard 52016-1 [11]. Finally, the wind speed and direction are used for the CEA dynamic infiltration calculation [12]. The CEA demand model produces hourly results on the demands for heating, cooling and electricity for the various services to be provided in each building.

The method described has been used for the assessment of an urban district project. The proposed Masterplan was simulated on an hourly basis for the coldest (CD) and hottest day (HD) in a typical year for two cases:

- Case 1: Simulation with CEA using microclimatic simulation results obtained with ENVI-met.
- Case 2: Simulation with CEA using atmospheric data input from weather station;

The results for space heating and cooling for each day were then compared to observe the impact of the inclusion of microclimate effects.

3. CASE STUDY DESCRIPTION

The method described in Section 2 has been used for the energy performance assessment of a redevelopment district project in Zurich. This project for a new university campus in the ‘Hochschulquartier’ (HQ) corresponds to the transformation of a dense and central area which hosts three educational institutions: ETH Zürich, the University of Zurich, and the University Hospital Zurich. The area is currently being redeveloped and densified to create additional floor space for the universities, hospital and complementary services. The spatial interventions are being planned taking into account building energy targets. However, it still appears very difficult to meet the limits imposed by the 2000 Watt Society targets to which the city has been committed since 2008 [13].

This case study is therefore selected as representative of complex district projects that aim for high energy efficiency and for which integrated tools can lead to the selection of spatial-energy sustainable solutions based on local environmental potential. The method presented here is used to investigate to what extent the microclimatic environment, caused by the transformation of urban structure and building geometry, impacts building energy performance.

The district configuration analysed in this study is based on the 2014 Masterplan for the area [14].

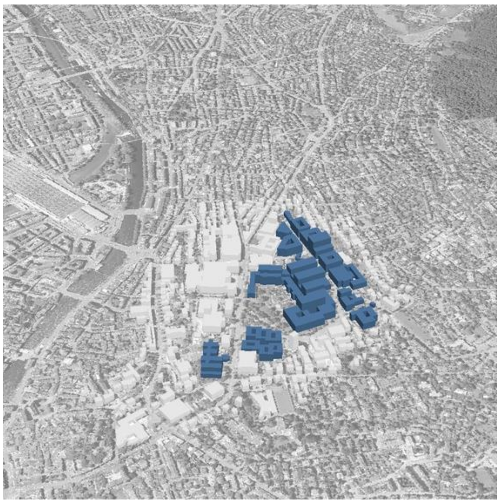

Figure 2: Hochschulquartier Masterplan 2014

3.1 Microclimate simulation and aggregation

In the first phase, the spatial model for the selected case study was built in ENVI-met (4.0). The new buildings were highlighted in the Masterplan and a study area was defined drawing a border that includes the buildings of interest, adjacent street canyons and the first adjacent building façades. From this border an offset area of 100m was taken as area of influence.

The three-dimensional spatial model was built in the ENVI-met simulation tool, including footprint and height of the buildings, topography and ground materials, on a grid unit 10x10x7m for the total selected area.

On this spatial model two simulations were run with ENVI-met for the coldest and hottest day of the typical year by forcing atmospheric boundary conditions on the basis of hourly data taken from a typical year for a nearby weather station from the software Meteonorm 7.0 [15]. Resulting wind speed, air temperature and relative humidity data were selected within a buffer of 10m from the buildings’ facades and aggregated in 3D buffers using each building’s code for use in CEA as weather input data.

3.2 Energy demand simulation

A model of the HQ case study was created in CEA based on information on building location, construction year and energy supply from local GIS data. The occupancy types for each building were obtained from a combination of GIS data and owner information, while data on energy-relevant retrofits for the main building components was scarce and thus was mostly estimated. Architectural properties and building materials for the existing stock were assigned based on site visits, whereas for new buildings these were assigned based on the CEA archetype database, which includes envelope properties for future constructions [9].

For the base case, typical year weather data from microclimate simulation, the exterior temperature, relative humidity and wind speed data were replaced for the HD and CD with the results from ENVI-met. Hourly heating and cooling demands for both cases were then calculated using the CEA demand module.

4. RESULTS

4.1. Comparison of microclimatic and meteorological data.

This section analyses the site-specific climate results for the HQ through comparison with the same measured variables derived by the selected weather station.

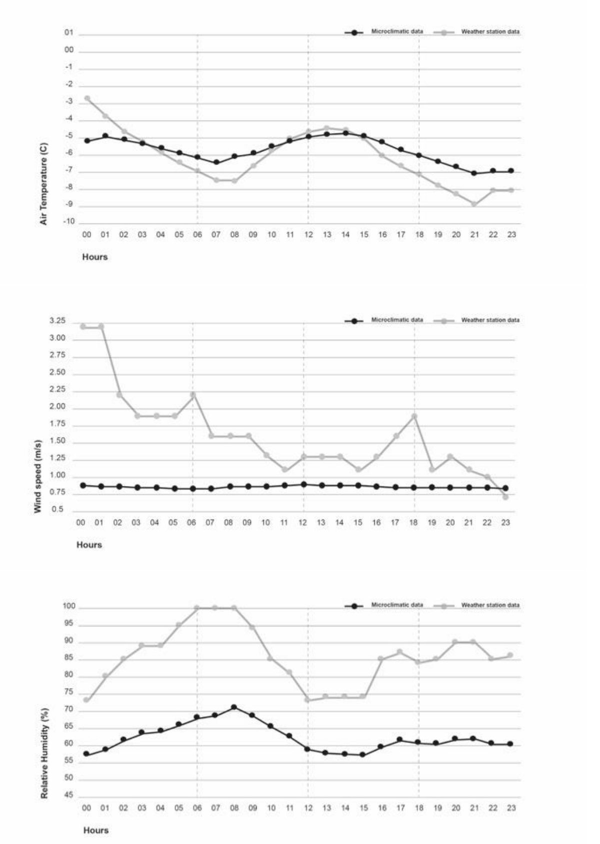

Figure 3: Comparison of the air temperature (top), wind speed (middle) and relative humidity (bottom) from the weather station and average air temperature around the buildings from ENVI-met for the CD.

For the coldest day, Fig.3 shows the comparisons for air temperature, wind speed and relative humidity data. Regarding air temperature, the results show that the urban environment has much smaller diurnal temperature curve compared to the rural environment. Temperature differences between the urban and rural environment are relatively small in the period between sunrise and sunset. During most of the day, the air temperatures in the urban environment are higher, showing a modest heat island effect of max to 2.5 °C, which manifests mainly during the night. The RH curve is rather flattened, with higher humidity levels occurring in the night and early morning, like at the rural site, as a result of the dropping temperatures.

In the hottest day, a significant variation between day and night time can be observed regarding average air temperature around the building units. Fig.4 shows that HQ local air temperatures during solar time are significantly lower than the rural ones, with a maximum difference of 3°C at 11 in the morning. In contrast, in the hours before sunrise and after sunset, the curves are inverted, registering lower rural air temperatures. Heat accumulated by urban surfaces and released during night hours contributes to the higher urban air temperatures of 25–26.5°C. In the second comparison it was found that the already low meteorological wind speed, which in the selected day reaches no higher than 0.5 m/s, significantly decreases in the studied area. Finally, data of relative humidity are analysed for the selected summer day. In comparison with the hourly data from the rural weather station, local relative humidity is found to be significantly higher during the daytime. The maximum variation can be observed in the middle of the day when the simulated humidity reaches 57%.

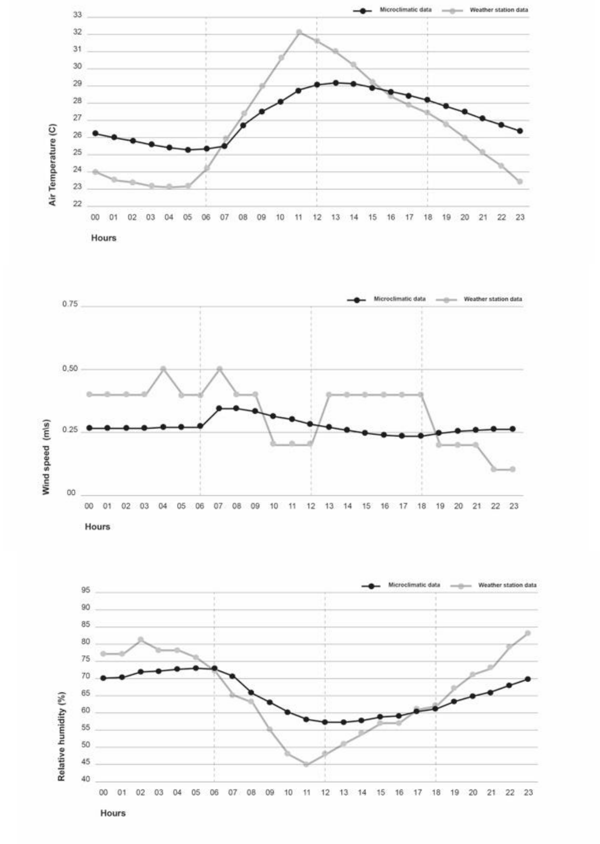

Figure 4: Comparison of the air temperature (top), wind speed (middle) and relative humidity (bottom) from the weather station and average air temperature around the buildings from ENVI-met for the HD.

4.2. Comparison of energy performance

Since all new buildings were assumed to be built to the Swiss energy efficiency standard Minergie, the space heating demand of the buildings in the area was on average extremely low at 14 kWh/m2-yr for the baseline case without microclimate. As expectable, older buildings had a higher demand, reaching as much as 167 kWh/m2-yr.

On the coldest day of the year, the average space heating demand for Case 2 was 147 Wh/m2 for all the buildings in the area. When microclimate effects were taken into consideration, the space heating demand was decreased on average by 2%. Similarly, the peak heating power for the entire district is decreased by 1.8%. The greatest overall decrease in the energy demand was seen in one of the remaining historical hospital buildings, where the space heating demand decreased from 1331 Wh/m2 for the baseline case to 1322 Wh/m2 for the case accounting for the effects of microclimate. Likewise, the peak heating power for this building on the coldest day of the year decreased from 244 W/m2 to 236 W/m2.

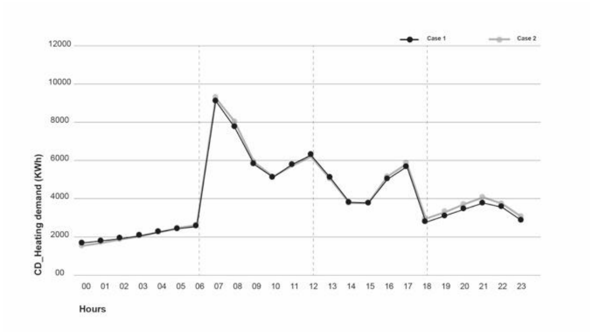

Figure 5: Comparison of hourly heating load in Cases 1 and 2 for the CD in a typical year.

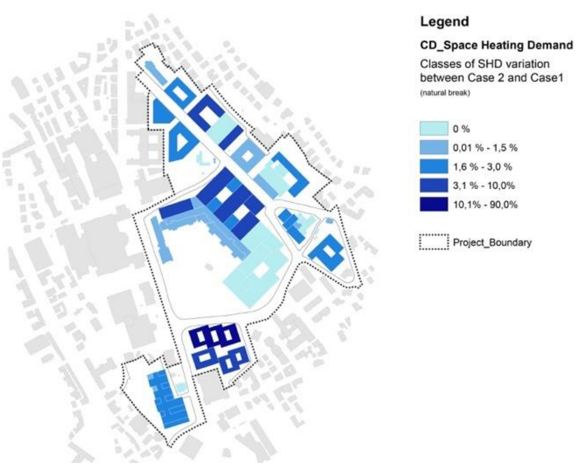

Figure 6: Percentage decreasing of space heating demand per square meter for the CD in Case 1 (compared with Case 2)

Due to the high level of insulation and the large internal gains in the buildings in the area, the space cooling demand in the HQ case is similarly significant, with 11 kWh/m2-yr on average. The University Hospital's main building complex has the highest cooling demands at 14 to 22 kWh/m2-yr, whereas older buildings either had a lower demand or no cooling system at all. On the hottest day of the year, the average space cooling demand in the baseline case without microclimatic effects was 185 Wh/m2. When microclimatic effects were considered, the overall demand in the area increased by 2%. The effect of microclimate on the peak cooling demand was more noticeable, with a 5% decrease in peak cooling power on the coldest day of the year.

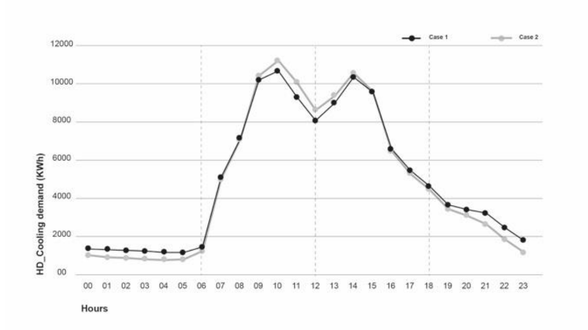

Figure 7: Comparison of the hourly cooling load in Cases 1 and 2 for the HD in a typical year.

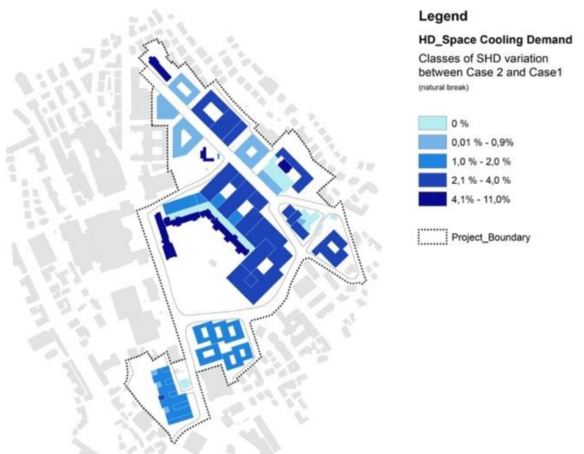

Figure 8: Percentage increasing of space cooling demand per square meter for the HD in Case 1 (compared with Case 2)

Older buildings showed a greater response to microclimate effects, while newer, highly insulated buildings had a much less significant effect in Case 1. For the cases including microclimate effects, the daily peak in the cooling demand is lowered for several buildings, however the higher night time temperatures cause several buildings to require cooling earlier than when microclimate effects are not accounted for. The new buildings of the University Hospital showed the greatest cooling power demand due to its high internal and solar gains and passive construction. Overall, the peak cooling power of the University Hospital's main building decreased from 17.9 W/m2 to 16.9 W/m2 when microclimate effects were taken into consideration.

5. DISCUSSION AND CONCLUSIONS

The study outlines a method for quantitative analysis of district-scale energy consumption taking into account the microclimatic effects created by the design of open and built space. A coupling approach that links the simulation tools ENVI-met and CEA is employed in a case study were urban development processes are expected to change microclimatic conditions and consequentially the energy performance of buildings.

From the previous results some general conclusions can be drawn. First, from a microclimate perspective, an atmospheric urban heat island phenomenon is observed in the area. Compared to the measured data from the weather station, local temperatures are higher during the night and wind speed is mitigated for the two days analysed. Comparison between the two Cases analysed shows that the consideration of microclimatic patterns leads to a general increased building cooling demand on the hottest day and a lower building heating load during the coldest day.

The previous results indicate the capacity of the developed method to analyse the energy performance of a complex urban district considering reciprocal influences between urban fabric configuration and local climate. In addition, it can provide a more realistic description of building energy performance and help designers in comparing the energy impact of different design solutions.

6. ACKNOWLEDGMENT

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