Energy and environmental analysis of urban environment: methodology and application of an integrated approach

F Salamone¹, L Belussi¹, L Danza¹, Antonello Di Nunzio², M Ghellere¹, I Meroni¹,

¹ Construction Technologies Institute - National Research Council of Italy (ITC-CNR), Via Lombardia 49, 20098, San Giuliano Milanese, Milan, Italy
² ENVI-MET GmbH, Kaninenberghöhe 2, 45136 Essen, Germany
* belussi@itc.cnr.it

Abstract. The new vision of Smart Cities drives policies regarding sustainability of urban environment in terms of reducing consumption, environmental impacts and improving energy efficiency and safety of building sector. The mutual interaction between buildings and the surrounding built environment can affect all these fields. In particular, the paper investigates this interaction in order to analyse the energy behaviour of buildings at urban scale and the effect on the outdoor comfort. To reach this goal a multi-level and multi-purpose model was developed based on a synergic and integrated bottom-up approach for both energy efficiency and outdoor comfort analysis. The energy analysis is based on the identification of reference buildings with known energy performances, defined sing information available at Public Authorities, statistical studies and data from field surveys. A multi-level parametric approach used for the outdoor comfort analysis allows to identify the Universal Thermal Climate Index (UTCI) and the related stress level of the district starting from the environmental data available at rural station. The model allows the estimation of the current energy and environmental behavior of the built environment and identifies possible renovation scenarios.

1. Introduction
Cities play a key role in sustainability policies aimed at reducing fuel consumption and environmental impacts and increasing energy efficiency in the building sector and improving human well-being within the built environment. The interactions between buildings and the built environment are studies since decades under different perspectives, from architectural [1] to engineering [2], from energy [3] to climatic [4] point of view. Due to these complexities, urban policies have to consider several characteristics related to buildings and the built environment as to provide the most suitable solutions following a holistic approach: in this paper the attention is paid on energy and outdoor thermal quality issues. In the last years a discipline aimed at assessing the performance of buildings at urban scale has been consolidated [5]. Urban Building Energy Models (UBEM) are frequently used for estimating the energy–saving potential in the building stock [6]. These models analyse the building stock from an energy point of view, considering the thermo-physical and energetic characteristics of the buildings and usually neglecting important variables that can affect the energy demand, such as the building behaviour [7]. UBEMs investigate the energy issue related to the building stock following two main approaches: the top-down approach in which the input are aggregated and the bottom-up approach in which the input are in disaggregated form. The bottom-up models are the most suitable decision support systems for local authorities thanks to the single building assessment of the energy consumption, up to district level or at the global urban scale as a function of the energy end-use. Meanwhile, the attention on the local microclimate and the outdoor comfort within the urban environment is growing due to the changing climate and increase of heat stress in cities [8]. Outdoor thermal comfort is often linked with the Urban Heat Island (UHI) phenomenon, although it depends on
the combined effect of other environmental variables, i.e., wind speed, humidity and radiation, besides air temperature [9]. The UHI effect on buildings consumption has been widely analysed [10]. Some researches integrate the effect of other environmental parameters highlighting the necessity of further improvements aimed at including the effect on outdoor thermal comfort [11], [12]. Scientific literature reports researches aimed at analysing the mutual interaction between buildings performance and built environment [13]. A wide investigated issue is the effect of urban environment on building energy behaviour [14] and its modelling [15]. To face this problem a common approach provide the coupling of building energy and microclimate simulation tools, where typically the outputs of the latter are used as boundary inputs of the former [16], [17].

The paper presents an integrated bottom-up approach based on energy and environmental analyses of the built environment and allows a diffuse energy diagnosis of the building stock and it can support the public administration to develop targeted energy policies. The paper describes the methodological approach and the preliminary results of the research activity, aimed at characterizing the energy and environmental performance of the urban fabric. The reliability of the system is tested on a real urban district located in Bologna.

2. Methods

The methodology is designed according to a bottom-up approach aimed at analysing the urban area from an energy and environmental point of view. The twofold analysis is carried out by considering the available information provided by open-source database, mainly made available by the regional territorial information system, needed to characterize both building stock and surrounding from a geometrical, morphological and functional point of view. Table 1 summarizes the open-source database consulted for the research and the data obtained. The use of these sources requires an initial validation of the data in order to avoid abnormal values, which could affect subsequent analyses.

| Database          | Data derived                                        |
|-------------------|-----------------------------------------------------|
| Municipal base map| Geometrical features (building height, volume, plan area), trees distribution |
| Town development plan | Prevailing intended use                             |
| Urban census      | Year of construction                                 |
| Weather station   | Rural weather data                                   |

The energy performance of buildings are defined according to the bottom-up framework proposed in [18], based on the definition of a reference buildings’ matrix. The environmental quality of the built surrounding is evaluated through the Universal Thermal Climate Index (UTCI), a thermal index defined within the cost action 730 and based on the multi-node ‘Fiala’ thermoregulation model [19].

2.1 Energy model

The aim of the energy model is the analysis of the energy behaviour of buildings at urban scale, in order to detect energy-intensive areas and provide possible refurbishment scenarios. The model provides the definition of a set of virtual buildings, grouped in a reference buildings matrix, obtained by clustering the characteristics of the building stock. The thermo-physical and energy characteristics of each reference building are derived from the TABULA building typology database for residential buildings and the register of Energy Performance Certificate (EPC) for non-residential ones. The energy performance of each virtual building is calculated in steady-state conditions.

Once the buildings’ matrix is defined, the data have to be assigned to each real building of the urban area. For this purpose, a two-step approach is followed. The first phase consists of the definition of the features of buildings at urban scale in compliance with the characteristics of the buildings matrix, derived from the open-source database available at each Italian public administration. In this way each
building can be characterized from the geometrical, functional point of view and year of construction, as summarized in Table 1. The second phase consists of the detection of the characteristics of the buildings through remote or in-field surveys in order to improve the quality of the information related to each building. For example it is possible to identify a multi-intended use within the same building fabric, possible refurbishment interventions and so on. At the end of this process, each building is uniquely characterized and may be associated with the respective category of the buildings’ matrix.

2.2 Environmental model

The aim of the environmental model is the analysis of the distribution of UTCI considering a multi-level approach. In particular, the environmental model consists of on a three-levels approach as a function of the required degree of detail of the analysis. The first level considers only the effect of direct sun/shade on people. The model does not account for spatial differences in both surface temperature across the urban area and wind speed. It considers the effect of the solar radiation, which is the largest driver of outdoor comfort during the daytime, and its effects on comfort and other rural environmental parameters as provided by the nearest weather rural station. The use of specific shapefiles related to trees distribution allows to analyse their shading effect and their influence on the outdoor thermal comfort. The core function of the model representing the second level is the Urban Weather Generator (UWG) [20], a python application that allows to morph rural weather data in order to reflect the canopy conditions, by considering a range of simplified urban properties: building geometry and intended use, urban materials, anthropogenic heat from traffic, vegetation coverage, atmospheric heat transfer from urban boundary and canopy layers. Finally, the third level is based on a series of components to connect Grasshopper3d, a parametric language, to ENVI-met, a software used for urban microclimatic analysis. The resulting calculation model allows the following aspects to be considered:

- solar radiation over the entire spectrum, from infrared to ultraviolet, respecting the shading, reflection and emission of radiation from the system of buildings and vegetation;
- transpiration, evaporation and latent heat flows from vegetation into the air;
- Complete simulation of the physical factors of plants, such as the photosynthesis reaction and its effects;
- surface temperature of the simulation area (buildings and ground);
- calculation of parameters such as the average radiant temperature and thermos-hygrometric indicators of the users of the area under analysis;
- airflow and turbulence, wind data.

3. Case study

The energy model is tested on a district of Bologna, Italy. The district consists of 580 units in total, where about 480 are buildings, with different intended use. About two-thirds of this set are single-use buildings. In particular residential is the prevalent intended use (70%). followed by the services (12%), commercial and educational (primary and secondary schools) buildings (respectively 7% and 5%). Finally, cultural and recreational and healthcare buildings are present with less than 10 units and no manufacturing buildings. Almost all multi-use buildings provides the coupling of residential and commercial use. Buildings were mainly built in the period 1920÷1975 which implies a construction type in “masonry” and “reinforced concrete”. Less of 5% of buildings were built in recent years.

4. Results

The application of the Energy model allows to quantify the energy behaviour of buildings within the considered district. In particular Figure 1 shows these results in terms of global primary energy (EPg), expressed in kWh/m²·y, defined by the sum of heating and DHW needs. The analysis of the numerical results shows an high percentage of buildings (about two thirds) with a primary energy between 250 and 300 kWh/m²·y. Less than 5% of buildings shows an EPg value lower than 100 kWh/m²·y. The result is in compliance with the characteristics of the district, built towards the end of the 19th century. Buildings are characterized with no or low-insulated envelopes and traditional heating systems (centralized gas boilers).
The Environmental model is tested on a square of the considered district with dimension of about 170x110 m where the prevalent intended use of buildings is the residential one. The first level of the environmental analysis allows to define the spatial distribution of UTCI considering the 3D district context, the solar path and rural environmental parameters (Figure 2). The UTCI considers the rural data about air temperature, relative humidity and wind speed. A specific component, described in [21], allows to adjust the values of mean radiant temperature for the mesh of points (grid size 1 m, distance from base surface 1 m) into which the surface of the urban context under analysis has been divided.

For the considered area and a specific period (a typical average values over one hour, 12 a.m. of august 6th) a maximum and minimum UTCI values equal to 40.19 °C and 30.40 °C, respectively, are calculated. The average UTCI is 34.95 °C and related standard deviation is equal to 3.58 °C.

The second level is based on the UWG component that allows to consider a range of simplified urban properties as input parameters (Table 2), thus allowing to define the canopy environmental conditions, starting from rural data on the basis of a Resistance/Capacitance model.

Table 2. UWG input parameters

| Traffic Parameters | Vegetation Parameters | Pavement Parameters | City | Building Typology |
|-------------------|----------------------|---------------------|------|------------------|
| Max Heat: 10 W/m² | Albedo: 0.35          | Albedo: 0.2         | Buildings height: 19 m | Midrise apartment pre 1980s |
Considering the same square and the specific period, the spatial distribution of UTCI is similar if compared with the previous case, however with lower maximum and minimum values equal to 38.87 °C and 28.96 °C, respectively. The average UTCI is 33.49°C and the related standard deviation is equal to 3.67 °C.

Level 3 is based on the environmental data provided by the UWG, managed by the ENVI-met model. Here below are presented the spatial distribution of UTCI for the considered area. The minimum value is of 31.22 °C and the maximum 43.89 °C, with an average of 39.72 °C and a standard deviation equal to 3.72 °C (figure 3a). Figure 3b reports the difference in terms of spatial distribution of the UTCI taking into account the rural environmental data, within the ENVI-met model.

5. Conclusions
The article describes a multi-objective methodology aimed at assessing the energy and environmental performance of the built environment by analysing the energy behaviour of buildings and the thermal condition of the surrounding. The methodology allows a deep characterization of the urban fabric with several information about the state of the buildings and their energy performance. These data are partially used as inputs by the environmental model to quantify the external thermal conditions through different tools and related approaches. Future developments will provide an in-depth investigation of the buildings characteristics based on on-site monitoring and surveys in order to guide the decision-making process towards efficient and effective interventions. Furthermore, an optimization procedure will be defined in order to optimize the outdoor thermal comfort analysis considering all the available data at the district level and to facilitate the user in choosing the best technical solutions for the building refurbishment.

Acknowledgments
The work described in the current paper is a partial result of the project RIGERS - Rigenerazione della città: edifici e reti intelligenti (project number SCN00040), supported by the National Operational Programme of Italy – Smart Cities and Communities.
References

[1] Futcher J, Mills G, Emmanuel R, and Korolija I 2017. Creating sustainable cities one building at a time: Towards an integrated urban design framework. *Cities*, **66**, 63–71.

[2] Rodler A, Guernouti S, Musy M, and Bouyer J 2018. Thermal behaviour of a building in its environment: Modelling, experimentation, and comparison. *Energy, Buildings*, **168**, 19–34.

[3] Fichera A, Frasca M, Palermo V, and Volpe R 2018. An optimization tool for the assessment of urban energy scenarios. *Energy*, **156**, 418–429.

[4] Touchaei A G, Akbari H, and Tessum C W 2016. Effect of increasing urban albedo on meteorology and air quality of Montreal (Canada)—Episodic simulation of heat wave in 2005. *Atmos. Environ.*, **132**, 188–206.

[5] Reinhart C F, and Davila C C 2016. Urban building energy modeling—A review of a nascent field. *Build. Environ.*, **97**, 196–202.

[6] Brogger M, and Wittchen K B 2018. Estimating the energy-saving potential in national building stocks—A methodology review. *Renew. Sust. Energ. Rev.*, **82**, 1489–1496.

[7] Happle G, Fonseca J A, and Schlueter A 2018. A review on occupant behavior in urban building energy models. *Energy, Buildings*, **174**, 276–292.

[8] Chen L, and Ng E 2012. Outdoor thermal comfort and outdoor activities: A review of research in the past decade. *Cities*, **29**, 118–125.

[9] Van Hove L W A, Jacobs C M J, Heusinkveld B G, Elbers J A, Van Driël B L, and Holtslag A M 2015. Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Build. Environ.*, **83**, 91–103.

[10] Li X, Zhou Y, Yu S, Jia G, Li H, and Li W 2019. Urban heat island impacts on building energy consumption: a review of approaches and findings. *Energy*, **174**, 407–419.

[11] Gros A, Bozonnet E, Inard C, and Musy M 2016. Simulation tools to assess microclimate and building energy—A case study on the design of a new district. *Energy, Buildings*, **114**, 112–122.

[12] Perera A T D, Coccolo S, Scartezzini J L, and Mauree D 2018. Quantifying the impact of urban climate by extending the boundaries of urban energy system modeling. *Appl Energy*, **222**, 847–860.

[13] Allegrini J, Orehouning K, Mavromatidis G, Ruesch F, Dorer V, and Evins R 2015. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renew Sust Energ Rev*, **52**, 1391-1404.

[14] Merlier L, Frayssinet L, Johannes K, and Kuznik F 2019. On the impact of local microclimate on building performance simulation. Part I: Prediction of building external conditions. *Build Simul.*, 1-12.

[15] Frayssinet L, Merlier L, Kuznik F, Hubert J L, Milliez M, and Roux J J 2018. Modeling the heating and cooling energy demand of urban buildings at city scale. *Renew Sust Energ Rev*, 81, 2318-2327.

[16] Yang X, Zhao L, Bruse M, and Meng Q 2012. An integrated simulation method for building energy performance assessment in urban environments. *Energy, Buildings*, **54**, 243-251.

[17] Topalar Y, Blocken B, Maiheu B, and van Heijst G J F 2018. Impact of urban microclimate on summertime building cooling demand: A parametric analysis for Antwerp, Belgium. *Appl Energ.*, **228**, 852-872.

[18] Belussi L, Danza L, Ghellere M, Guazzi G, Meroni I, and Salamone F 2017. Estimation of building energy performance for local energy policy at urban scale. *Energy Proced.*, **122**, 98–103.

[19] Fiala D, Havenith G, Bröde P, Kampmann B, and Jendritzky G 2012. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *Int J Biometeorol.*, **56**(3), 429–441.

[20] Nakano A, Bueno B, Norford L, and Reinhart C F 2015. Urban Weather Generator—A novel workflow for integrating urban heat island effect within urban design process. *Proceedings of building simulation 2015*. December 7-9, Hyderabad.

[21] Arens E, Hoyt T, Zhou X, Huang L, Zhang H, Schiavon S 2015. Modeling the comfort effects of short-wave solar radiation indoors. *Build. Environ.*, **88**, 3-9.