*Acta Polytechnica CTU Proceedings* **38**:145–150, 2022
https://doi.org/10.14311/APP.2022.38.0145


# SUPPORTING SUSTAINABLE POLICIES THROUGH AN URBAN ENERGY-ENVIRONMENTAL MODEL AND A MULTI-CRITERIA ANALYSIS: A CASE STUDY IN AN ITALIAN PROVINCE

Lorenzo Belussi*, Benedetta Barozzi, Alice Bellazzi, Ludovico Danza, Anna Devitofrancesco, Matteo Ghellere, Francesco Salamone

*ITC-CNR, via Lombardia 49, 20098 San Giuliano Milanese, Italy*
* corresponding author: belussi@itc.cnr.it

Abstract. Public Authorities (PAs) need to define cross-cutting strategies for urban planning including policies for sustainable and energy-efficient buildings and innovative urban solutions. The article presents a decision support tool that combines an Urban Energy Environmental Model (UEEM) and a Multi-Criteria Analysis (MCA) to support the development of sustainable local policies. The UEEM, developed with a bottom-up approach incorporating energy and environmental items, provides a representation of the performance of local urban areas and quantifies the impact of new interventions in expansion areas. The UEEM is based on the definition of virtual archetypes built on the characteristics of the area under consideration. 92 building archetypes and 40 urban archetypes are developed. The energy performance of each building archetype is calculated with a dynamic simulation tool. The environmental performance of urban areas (overheating risk and outdoor thermal comfort) is analysed through a Grasshopper-based parametric model. In addition, soil permeability is calculated. The UEEM results are aggregated into a single index using the MCA, providing a Municipal Rating Index (MRI). The weights of the MCA are estimated through the Analytical Hierarchy Process (AHP) based on a survey submitted to local stakeholders (municipalities, environmental associations, experts). The model is applied to the province of Monza and Brianza in northern Italy.

Keywords: Urban planning, urban energy environmental model, multi-criteria analysis, analytical hierarchical process.

## 1. Introduction

City planning has raised several environmental, social and economic issues that Public Authorities (PAs) have often tried to address with inadequate tools, with the result that urban areas are often a collection of environmental, social and economic problems [1]. To make them sustainable, it is necessary to develop and to adopt new planning approaches that include a multi-sectoral scope [2]. This requires a comprehensive knowledge of the energy and material exchanges that characterize the urban metabolism of cities or urban areas [3] and the need of adequate tools to quantify and analyse these flows for the formulation of sustainable planning and policy recommendations [4]. Multidimensional approaches and specific methods that can assess and summarise multiple aspects of urban planning can help to address these issues. Among the several assessment methods applied [5], the Multi-Criteria Analysis (MCA) has been widely used [6]. In [7], the authors describe a decision-making system based on Multicriteria Decision Analysis (MCDA) to support policy makers in defining resilient territorial systems: the result is a single index that combines seven indicators to identify the resilience class of municipalities in Portugal. The MCDA to support the sustainable development of cities, described in [8], is based on a composite index that aggregates 35 energy and environmental indicators. The results of these studies have practical implications for the decision-making process providing stakeholders with a tool for defining policies developed starting from the real needs of cities and/or urban areas. Such studies are typically based on aggregated data for the representation of urban performance. This article combines an Urban Energy and Environmental Model (UEEM) developed in a previous research [9, 10] with an MCA, developing an integrated Decision Support System (DSS) for representing the performance of a local urban area. The proposed DSS quantifies the impact of new interventions in expansion areas too. Considering that UEEM is based on a bottom-up approach moving from the definition of specific virtual archetypes (Figure 1) stated on information available to PAs and statistical studies, the model provides an estimation of the current energy performance of the building stock, in terms of primary energy consumption and $CO_2$ emissions, as well as the environmental characteristics of the urban building fabric in terms of potential overheating. The method is used to evaluate the impact of new neighbourhoods in a northern Italian province.

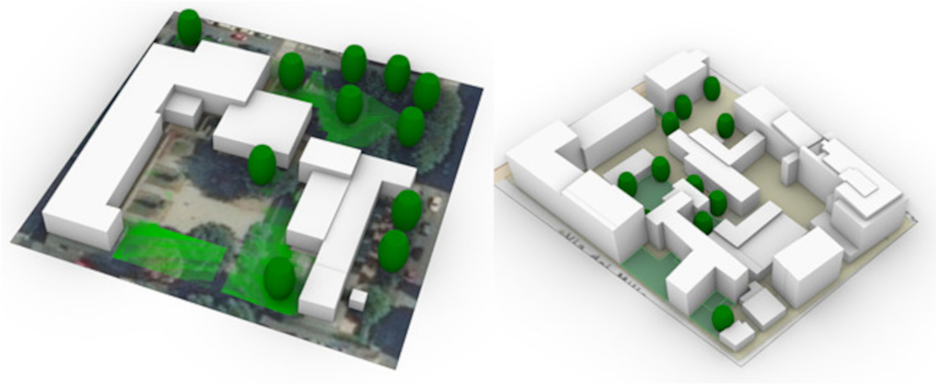

Figure 1. Example of 3D model built from shapefile.

## 2. Materials and method

This study combines a UEEM and the MCA to support decision makers in the sustainable development of new neighbourhoods. The UEEM method was developed using a bottom-up approach, from single components (buildings and neighbourhoods) to the overall urban area. The twofold analysis is performed by considering the available information from open-source database, mostly from the regional territorial information system, for the geometrical, morphological and functional characterization of the building stock and the surrounding urban areas. The UEEM is applied for the representation of the energy and environmental performance of urban areas. The outcomes of the UEEM are managed by MCA for the definition of an aggregated index called Municipal Rating Index (MRI) for the identification areas suitable for new sustainable urban development. The following section presents the overall model and the case study.

### 2.1. Case study

The case study is the Province of Monza and Brianza, with an area of 405 km$^2$, located to the north-east of the city of Milan in the Lombardy region, divided into 55 municipalities with an anthropized soil ratio of 41 %, due to the intensive residential and industrial urbanization that has been going on since the 70s. The analysis uses open vector and raster data retrieved from the geographic portal of Lombardy region [11]. The available vector data refer to building properties, presence of vegetation and soil use through the Corine Land Cover classification [12] implemented by the regional map "Destinazione d'Uso dei Suoli Agricoli e Forestali – Agricultural and forest land use" (DUSAF) [13] for the year 2018 (version 6.0). Raster data provide the buildings footprint at different time periods (Regional Technical Map – CTR) [14]. Analyses are also performed at sub-municipal level. In this case, the boundaries of the Territorial Census Sections (TCS) provided by ISTAT (National Institute of Statistics) are used [15]. The management and processing of the georeferenced data is performed with the GrassGIS software [16].

The MCA evaluation of the building expansion policies of the municipalities is focused on the energy and environmental performances and is based on the intervention scenarios defined for the transformation areas identified by each municipality. The following aspects related to the transformation are considered:

- All design hypotheses comply with the predictions and requirements of the municipal development plans concerning urban parameters (building typology, height, distances, coverage ratio, etc.).
- The energy performance of the planned buildings complies with the requirements of the current legislation for near Zero Energy Buildings (nZEBs).
- For each planned building use, the shape of planned buildings corresponds to the one most commonly used after the last CTR recognition (2003 to date).
- Building footprint and vegetation soil coverage fraction equals the Territorial Census Section-(TCS) mean values of the municipalities which have the same planned building use.

### 2.2. Energy and environmental models

The building stock is classified according to the following features:

- Building typologies: Residential, Office, School, Commercial, Supermarket and Industry.
- Construction period: before 1976, 1976–1990, 1991–2005, after 2005, considered as milestones in the Italian legislation having affected the thermal and energy performance of buildings over the years.
- Urban context: dense (distance between buildings $\leq$ 10 m), open (distance between buildings $\leq$ 20 m) or isolated (distance between buildings $>$ 20 m) based on available local georeferenced data.

The granularity of buildings with residential use, offices and schools is further enhanced, due to a more accurate characterization of the building stock representative of the areas considered in the case study. Residential buildings are classified into four categories (single family, detached house, multifamily building and apartment block) with respect to predefined shape

| Intensity of importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two attributes contribute equally to the objective |
| 3 | Moderate importance | Experience and judgment slightly favour one over another |
| 5 | Strong importance | Experience and judgment strongly favour one over another |
| 7 | Very strong importance | An attribute is strongly favoured |
| 9 | Extreme importance | The evidence favouring one attribute over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values | When compromise is needed |

Table 1. Judgement scale proposed by Saaty [17].

ratio (S/V) threshold values: 0.38, 0.57 and 0.72. Offices are classified depending on the number of floors: $\leq 2$ floors for "low-rise", $> 2$ floors for "medium-rise". Finally schools are identified based on their location: "compact" in a dense area or large and "isolated" in the suburbs. By combining all the features, a matrix of 92 archetypes is defined. Each reference building is then characterized by the performance of the envelope, HVAC, energy carriers and occupancy profile found in standard references or EU projects. The primary energy consumption [kWh] and $CO_2$ emissions [kg $CO_2$] of the archetypes, expressed per square meter of building area, are calculated using the EnergyPlus simulation tool and its interface DesignBuilder®, including heating, cooling, domestic hot water production, lighting and ventilation energy services. Finally, the archetypes are applied to the existing buildings and aggregated at different spatial scales: building, TCS, municipality and aggregation of municipalities scale. The aggregations provide a comprehensive and structured knowledge of the performance of the area. Starting from the building level, the aggregation of data is done with the weighted average of KPIs (Key Performance Indicators) within a given area.

The environmental model assesses the overheating risk and the permeability of the area. The urban area is classified according to the land use typology defined by DUSAF. The parameters used to characterize the areas are defined in accordance with the Urban Weather Generator (UWG) engine [18], which considers both building morphology and the land cover characteristics. In relation to the overheating assessment performed with the UWG tool analysis, the urban areas warmer than 1.80 °C compared to the reference rural areas are considered "overheated".

The permeability is assessed starting from the Vegetation Coverage Ratio (VCR), assigning an average runoff coefficient to each census area defined by DUSAF. As a reference, runoff coefficients are defined by the American Society of Civil Engineer and the Water Environment Federation, calculated for return periods of 10 years or less and corresponding to the main characteristics of the area [19]. For each rural typology area, excluding water bodies, the value 0.15 has been taken as a reference. For anthropized areas, runoff index is determined by a linear interpolation between 0.15 and 1.00 in proportion to the mean VCR value of the class (from 100 % to 0 %).

Finally, the maps of overheated areas and the runoff index are rasterized at high resolution (0.75 m/px) to allow the calculation of the environmental KPIs at the municipality level: the ratio between non-overheated areas and municipality area (overheating risk) and the mean runoff index (permeability).

### 2.3. Multi-Criteria Analysis

MCA is used to identify and compare different policy options and assess their effects and impacts. In this study, the MCA is applied to identify the most suitable areas for new urban development. combining the scores of different indicators into a single municipal index, Moreover, the index is used to evaluate the impact of new urban settlements with respect to the baseline scenario. The Analytic Hierarchy Process (AHP) is the method used to develop the MCDA system [20]. This method consists of decomposing a problem into a hierarchy and comparing the attributes, two at a time, with respect to their effect on the other attributes. Seven criteria concerning energy and environmental performance of each municipality were considered in the analysis:

(1.) Building Energy Consumption;

(2.) Anthropogenic $CO_2$ Emissions (buildings and transport);

(3.) Urban Overheating;

(4.) Soil Imperviousness;

(5.) Soil Consumption;

(6.) Areas of Environmental Interest;

(7.) Areas of Agricultural Interest.

The criteria are compared to measure their relative importance with respect to the main goal based on the following question: "How important is attribute A with respect to attribute B?". The comparison is made using the nine-points judgment scale reported in Table 1. Each criterion is scaled on a five-point

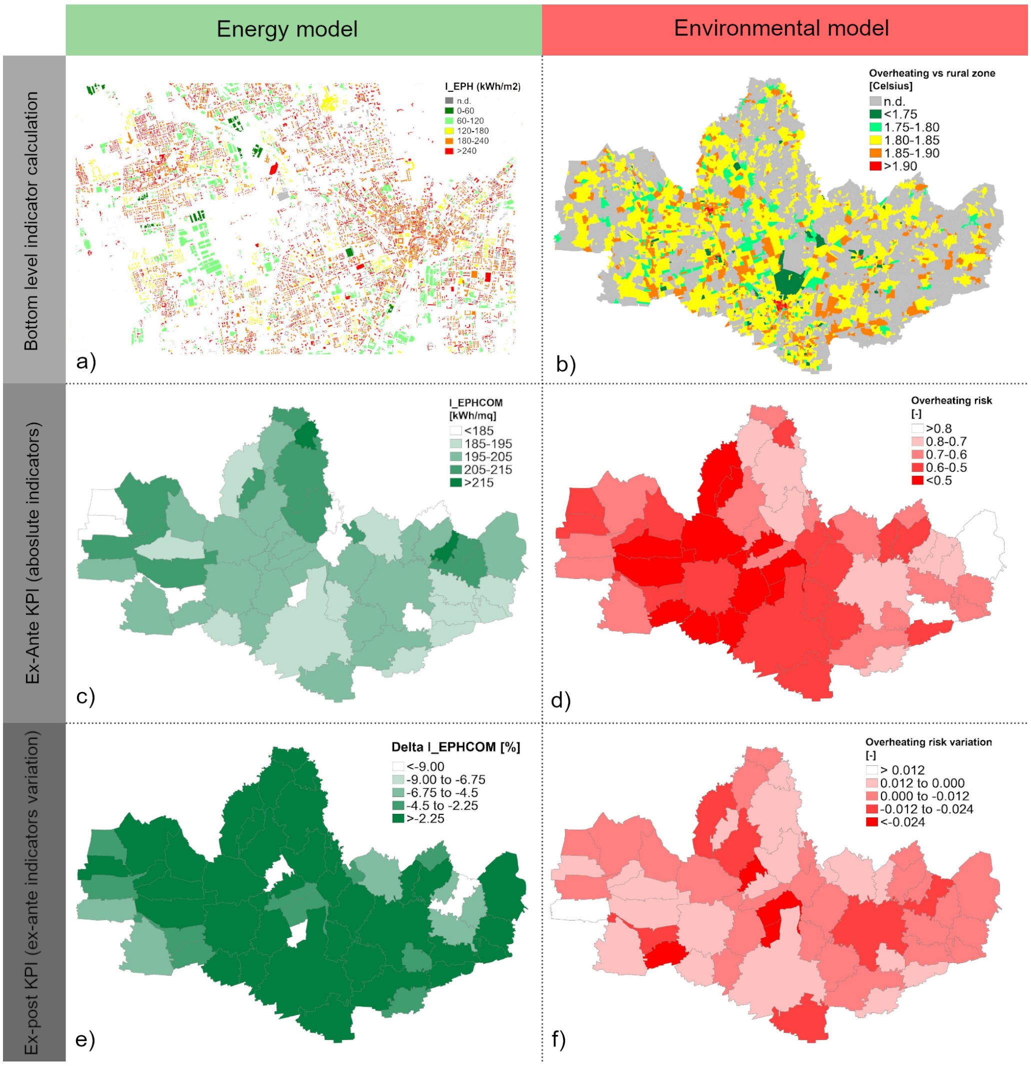


FIGURE 2. Example of a KPI assessment for energy and environmental analysis. In ex-ante and ex-post analysis, the more colourful the municipality, the worse the performance.

scale with a min-max procedure. Intermediate values are not considered.

A number of stakeholders participate together in the decision-making process and in this case four groups were involved:

- Province's Employees (P).
- Mayors and Technicians from involved Municipalities (M).
- Scientists involved in energy and environmental research (S).
- Professional Associations (A).

A questionnaire is submitted to each stakeholder group reporting the pairwise comparison of the indicators.

The analysis of the completed questionnaires led to the calculation of the weight of each group followed by the definition of the overall weight of each criterion for the calculation of the MRI.

The individual judgments have to be aggregated in order to fulfil the process. Two main approaches can be applied for this task: Aggregating Individual Judgments (AIJ) when individuals in a group act to merge their own preferences to reach a synthetic judgment, and Aggregating Individual Priorities (AIP) when the individuals act for themselves [21]. In the present work the AIJ approach is applied and the geometric mean is used for the aggregation process.

## 3. RESULTS AND DISCUSSION

The KPIs are calculated for each municipality using the bottom-up approach to point out the MCA of the current state of the territory (ex-ante scenario) and of the intervention scenario (ex-post scenario). Figure 2 explains the calculation process for the KPIs of energy (e.g. energy consumption) and environmental (e.g. overheating risk) analyses.

The KPIs for the new scenarios are represented as the variation (percentage or absolute value) with respect to the baseline scenario. As shown by the energy assessment (Figure 2c), most of the municipalities have on average a high energy index (195–205 kWh/m$^2$y) and, as a consequence, show a high $CO_2$ consumption.

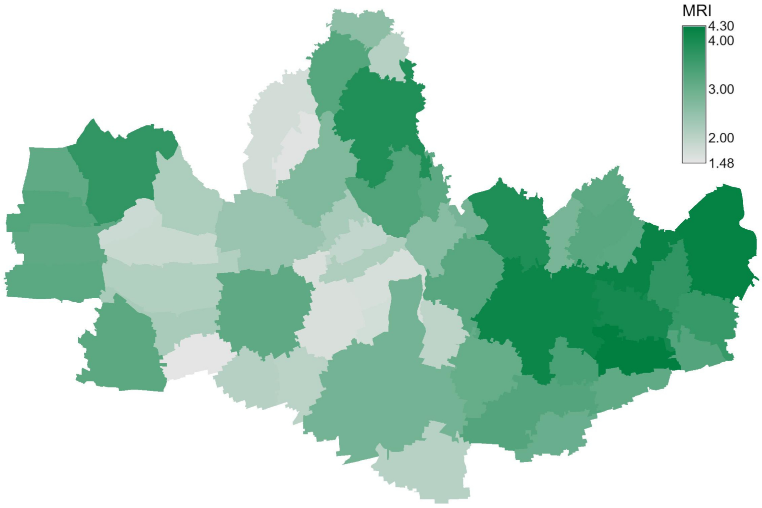


Figure 3. MRI map.

| n | Criteria | Weight (S) | Weight (P) | Weight (A) | Weight (M) | Mean Weight |
|---|---|---|---|---|---|---|
| 1 | Building energy consumption | 15.0 % | 4.2 % | 24.5 % | 15.4 % | 13.2 % |
| 2 | Anthropogenic $CO_2$ emissions | 26.5 % | 7.5 % | 15.6 % | 13.1 % | 15.1 % |
| 3 | Urban overheating | 10.6 % | 4.3 % | 8.3 % | 9.0 % | 8.1 % |
| 4 | Soil imperviousness | 12.9 % | 13.8 % | 9.1 % | 14.1 % | 13.1 % |
| 5 | Soil consumption | 9.0 % | 17.0 % | 16.6 % | 14.7 % | 14.8 % |
| 6 | Areas of environmental interest | 14.6 % | 26.5 % | 15.0 % | 19.9 % | 20.0 % |
| 7 | Areas of agricultural interest | 11.4 % | 26.8 % | 11.0 % | 13.8 % | 15.7 % |

Table 2. Weighting factors.

This is due to the old municipal building stock plus in addition to the high extension of non-residential buildings with a high electrical consumption due to lighting and HVAC systems. Thanks to the compliance of new buildings with ZEB requirements, the transformation scenario ensures a slight decrement in the municipal energy index (Figure 2e).

The ex-ante environmental assessment (Figure 2d) points out a medium-high overheating risk (deep red-coloured municipalities) due to the high urbanization rates of the past. The assessment of the transformation scenarios (Figure 2f) points out differences in overheating risk management between municipalities. Permeability performances follow the same trend of the overheating risk.

The analysis of the questionnaires completed by the stakeholders led to the calculation of the weights for each criterion, as shown in Table 2.

The analysis shows that Areas of Environmental Interest account for 1/5 of the overall weights and they represent the highest priority area. Following and very close to each other are Areas of Agricultural Interest, Anthropogenic $CO_2$ Emissions, Soil Consumption, Building Energy Consumption and Soil Imperviousness. Urban Overheating ranks last and far below the others.

The mean weight is calculated as the geometric mean among (of) the weights of each stakeholder. MRI is calculated as the sum of calculated and weighted indicators in order to assess each Municipality (Figure 3).

## 4. Conclusions

The paper develops a simplified model for analysing the current energy and environmental performance of urban areas supporting PAs in evaluating the impact of new expansion areas and driving future urban policies. This UEEM is applied to the case study of the Monza and Brianza province but it can be replicated in different contexts. It uses information on buildings and urban areas provided by PAs, as well as indicators and calculation methods that are widely accepted and used. The KPIs can be modified to meet the needs of the PAs.

The model can support planning, monitoring and visualization of activities. In the planning phase it supports decisions to maximize benefits while reducing negative impacts of new interventions at building and urban scale (energy and $CO_2$ emissions, overheating risk reduction, improvement of green solutions applications, optimization of run-off coefficient and urban comfort). The model allows monitoring of the variation of energy and environmental indicators over time and the impact of the different scenarios at urban scale.

The breakthrough of this study consists in the detailed evaluation of the performance of new urban areas in order to identify development strategies to achieve the energy and environmental targets of 2030 and 2050. Future developments will provide the evaluation of the customized UWG model to better reflect the Italian building stock against field data, the integration of new indices for a better description of the performance of urban areas including social and economic issues, as well as the definition of a municipal rating index used for the purposes of aggregating energy, environmental, economic and social data.

## REFERENCES

[1] F. C. Caldatto, S. C. Bortoluzzi, E. Pinheiro de Lima, S. E. Gouvea da Costa. Urban sustainability performance measurement of a small Brazilian city. *Sustainability* **13**(17):9858, 2021. https://doi.org/10.3390/su13179858.

[2] R. Roggema. The future of sustainable urbanism: a redefinition. *City, Territory and Architecture* **3**:22, 2016. https://doi.org/10.1186/s40410-016-0052-y.

[3] S. Ulgiati, A. Zucaro. Challenges in urban metabolism: Sustainability and well-being in cities. *Frontiers in Sustainable Cities* **1**:1, 2019. https://doi.org/10.3389/frsc.2019.00001.

[4] A. González, A. Donnelly, M. Jones, et al. A decision-support system for sustainable urban metabolism in Europe. *Environmental Impact Assessment Review* **38**:109–119, 2013. https://doi.org/10.1016/j.eiar.2012.06.007.

[5] C. Cortinovis, D. Geneletti, K. Hedlund. Synthesizing multiple ecosystem service assessments for urban planning: A review of approaches, and recommendations. *Landscape and Urban Planning* **213**:104129, 2021. https://doi.org/10.1016/j.landurbplan.2021.104129.

[6] K. Ogrodnik. Multi-criteria analysis of design solutions in architecture and engineering: Review of applications and a case study. *Buildings* **9**(12):244, 2019. https://doi.org/10.3390/buildings9120244.

[7] V. Assumma, M. Bottero, E. De Angelis, et al. A decision support system for territorial resilience assessment and planning: An application to the Douro Valley (Portugal). *Science of The Total Environment* **756**:143806, 2021. https://doi.org/10.1016/j.scitotenv.2020.143806.

[8] R. Carli, M. Dotoli, R. Pellegrino. Multi-criteria decision-making for sustainable metropolitan cities assessment. *Journal of Environmental Management* **226**:46–61, 2018. https://doi.org/10.1016/j.jenvman.2018.07.075.

[9] F. Salamone, L. Belussi, L. Danza, et al. Energy and environmental analysis of urban environment: methodology and application of an integrated approach. *IOP Conference Series: Materials Science and Engineering* **609**(7):072018, 2019. https://doi.org/10.1088/1757-899X/609/7/072018.

[10] L. Belussi, L. Danza, M. Ghellere, et al. An integrated tool for the energy and seismic diagnosis and refurbishment of buildings at urban scale. In *Proceedings of the 16th IBPSA Conference*, pp. 3226–3233. 2019. https://doi.org/10.26868/25222708.2019.210290.

[11] Regione Lombardia. Geoportale. [2021-10-04], https://www.geoportale.regione.lombardia.it/en-GB/home.

[12] G. Büttner, J. Feranec, G. Jaffrain, et al. The CORINE Land Cover 2000 project. In *EARSeL eProceedings*, vol. 3, pp. 331–346. 2004.

[13] Regione Lombardia. [2021-10-04], https://www.regione.lombardia.it/wps/portal/istituzionale/HP/DettaglioServizio/servizi-e-informazioni/Enti-e-Operatori/Territorio/sistema-informativo-territoriale-sit/uso-suolo-dusaf/uso-suolo-dusaf.

[14] Regione Lombardia. Geoportale – Sezioni CTR. [2021-10-04], https://www.geoportale.regione.lombardia.it/en-GB/download-ctr.

[15] Istat. Basi territoriali e variabili censuarie. [2021-10-04], https://www.istat.it/it/archivio/104317.

[16] M. Neteler, M. H. Bowman, M. Landa, M. Metz. GRASS GIS: A multi-purpose open source GIS. *Environmental Modelling & Software* **31**:124–130, 2012. https://doi.org/10.1016/j.envsoft.2011.11.014.

[17] T. L. Saaty. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology* **15**(3):234–281, 1977. https://doi.org/10.1016/0022-2496(77)90033-5.

[18] B. Bueno, L. Norford, J. Hidalgo, G. Pigeon. The urban weather generator. *Journal of Building Performance Simulation* **6**(4):269–281, 2013. https://doi.org/10.1080/19401493.2012.718797.

[19] Runoff coefficients for InfoSWMM, InfoSWMM SA, ICM and XPSWMM. [2021-10-04], https://swmm5.org/2017/10/12/runoff-coefficients-for-infoswmm-infoswmm-sa-icm-and-xpswmm/.

[20] T. L. Saaty. What is the analytic hierarchy process? In *Mathematical Models for Decision Support*, pp. 109–121. 1988. https://doi.org/10.1007/978-3-642-83555-1_5.

[21] E. Forman, K. Peniwati. Aggregating individual judgments and priorities with the analytic hierarchy process. *European Journal of Operational Research* **108**(1):165–169, 1998. https://doi.org/10.1016/S0377-2217(97)00244-0.