

Assessment and Mapping of the Urban Heat Island Effect: A Preliminary Analysis on the Impact on Urban Morphology for the City of Turin, Italy

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Edited by

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Table of Contents

Preface	ix
Analytical Model (SAM 2.0): A New Frontier in Open-Source Building Energy Simulation <i>Michał Dengusiak, Jakub Ziolkowski, Michalina Dengusiak</i>	1
Synthetic Indices for Comfort Assessment: An Application to a Historical Building in Catania / Andrea Longhitano, Gianpiero Evola, Vincenzo Costanzo, Francesco Nocera	9
Data-Driven Digital Twinning of Ventilation Systems for Performance Optimization: A University Building Case Study <i>Andres Sebastian Cespedes Cubides, Jakob Bjørnskov, Muhyiddine Jradi</i>	17
Computational Cost Reduction of a Simulation-Based Optimization Process Through Machine Learning Methods: Neural Networks vs. Random Forest <i>Iuri Praça Verginio, Rafael de Paula Garcia, Mario Alves da Silva, Joyce Correia Carlo</i>	25
Normalization Method of Building's Actual Energy Consumption for Normalized Building Energy Benchmarking <i>Deuk-Woo Kim, Dong-Hyuk Yi, Cheol-Soo Park</i>	31
Simulator for Predicting Vertical Illuminance of Window With External Venetian Blind <i>Seon-Young Heo, Young-sub Kim, Seon-Jung Ra, Cheol-Soo Park</i>	39
Modelling Solar Disability Glare Reflected off Modern Building Facades <i>Matthew J. Glanville, Pallava R. Kodali, Mohammed Alsailani, Roberto P.M. Neto</i>	49
Energy Modelling and Calibration of a Controlled Environment Agriculture Space in a Cold Climate Using Building Performance Simulation Tools <i>Gilbert Larochelle Martin, Danielle Monfet</i>	57
Microclimate Conditions in the SS. Salvatore Church of Bologna <i>Haruna Saito, Massimiliano Manfren, Kristian Fabbri, Maria Cristina Tommasino, Lamberto Tronchin</i>	65
The Impact of Thermal Zone Resolution on the Energy Simulation Results of Complex Buildings <i>Christiane Berger, Ardeshir Mahdavi</i>	71
Development and Calibration of an Urban Building Energy Model for the City of Padua <i>Jacopo Vivian, Enrico Pratavia, Gianmarco Bano, Angelo Zarrella</i>	77
ClustEnergy OpTool: An Open Tool for Assessing the Energy Flexibility Provided by Clusters of Buildings <i>Patricia Ercoli, Alice Mugnini, Fabio Polonara, Alessia Arteconi</i>	85
The Role of Dynamic Primary Energy Factors (PEFs) in Building Performance Assessment: A Case Study <i>Matteo Bilardo, Riccardo Oldini, Enrico Fabrizio</i>	95
Modeling a Dew Point Indirect Evaporative Cooling System for TRNSYS Building Simulations: Proposal and Validation <i>Alessandra Urso, Gianpiero Evola, Francesco Nocera, Vincenzo Costanzo, Ana Tejero-Gonzales, Eloy Velasco-Gomez</i>	105
Acoustic Correction of the Regional Theatre of Bejaia (Algeria) <i>Feriel Saidane, Gino Iannace</i>	113
From Theatre to Cinema to Theatre Again: The Acoustic History of the Vittorio Emanuele II Theatre of Benevento Through Simulations <i>Gino Iannace, Antonella Bevilacqua, Umberto Berardi</i>	119
Economic and Environmental Optimization of Retrofitting Options for a Community Building. A Case Study from Förslöv-Grevie Parish, Sweden <i>Azadeh Hana Hassanzadeh, Sepideh Rabie, Marko Ljubas, Henrik Davidsson, Dennis Johansson</i>	125
Installation of Reflecting Panels in the Main Church of Aversa <i>Silvana Sukaj, Amelia Trematerra, Ilaria Lombardi, Giovanni Amadasi, Luigi Guerriero</i>	133

Building Information Modeling (BIM) and Building Energy Modeling (BEM): Interoperability and Interactive Data Representation for the Energy Management of the Existing Buildings <i>Ilaria Giannetti, Cristian Tolù, Giulia Scimia, Gianluigi Bovesecchi, Pier Paolo Valentini, Cristina Cornaro</i>	141
Modelling of Aquifer Thermal Energy Storage Connected to Hospital Buildings: A Case Study in Denmark <i>Mohammed Burhanuddin Rabani, Alessandro Maccarini, Michael Wetter, Alireza Afshari</i>	149
Analysis of Energy Consumption Scenarios of the Italian Residential Building Stock <i>Enrico Prativiera, Jacopo Vivian, Francesca Gaudino, Angelo Zarrella</i>	157
Automating Solar Shading Control in Residential Buildings Located in a Temperate Climate: A Household-Specific Decision <i>Lotte Van Thillo, Stijn Verbeke, Amaryllis Audenaert</i>	165
Simulating the Microclimate of a Pilot Greenhouse for the EU Project REGACE on Innovative Agri-Voltaic Technology <i>Cristina Cornaro, Marcello Petitta, Gianluigi Bovesecchi, Paolo Miraglia Fagiano, Catalin Voinea, Walter Fornari, Catherine Baxevanou, Dimitrios Fidaros, Chryssoula Papaioannou, Nikolaos Katsoulas</i>	175
Building Archetypes Supporting the National Building Renovation Plan <i>Matteo Piro, Ilaria Ballarini, Vincenzo Corrado</i>	183
Integration of Machine Learning-Based CIE Standard Skies Model With Daylight Simulation for Building Energy Performance Analysis <i>Emmanuel Imuetinyan Aghimien, Ernest Kin-wai Tsang, Danny Hin-wa Li, Zhenyu Wan</i>	191
A Design Assistant Tool for Optimised Building Energy Retrofit <i>Ilaria Di Blasio, Julius Emig, Dietmar Siegele, Dominik T. Matt</i>	199
A Simulation Study on the Performance of Machine Learning Daylight-Linked Lighting Control Under Urban Topography <i>Ernest Kin-wai Tsang, Emmanuel Imuetinyan Aghimien, Danny Hin-wa Li, Zhenyu Wang</i>	207
BIM2FEM: From Building Information Modelling to Finite Element Analysis – An Automated Open Source-Based Workflow <i>Julius Emig, Dietmar Siegele, Dominik T. Matt</i>	215
Hygrothermal Analysis of Most Common Historical Slabs in Hungary <i>Fanni Petreševics, Balázs Nagy</i>	223
Energy Flexibility Study of a Hotel Using TRNSYS <i>Michele Libralato, Giovanni Cortella, Paola D'Agaro</i>	233
The Impact of Classroom Acoustics on Student Well-Being and Noise Disturbance at the University of Pescara, Italy <i>Samantha Di Loreto, Alessandro Ricciutelli, Leonardo Guglielmi, Sergio Montelpare</i>	241
Environmental Quality Analysis in School Environment by Measurements and Numerical Methods <i>Leonardo Guglielmi, Samantha Di Loreto, Matteo Falone, Mariano Pierantozzi</i>	249
A Comparative Analysis of Simplified Calculation Procedures for Assessing the Energy Losses of Heating Emission Systems <i>Franz Bianco Mauthe Degerfeld, Ilaria Ballarini, Vincenzo Corrado</i>	257
Simplified and Fully Detailed Dynamic Building Energy Simulation Tools Compared to Monitored Data for a Single-Family NZEB House <i>Ana Paola Rocca Vera, Giovanni Cortella, Paola D'Agaro</i>	265
A Building Renovation Concept Based on a Low-Temperature Geothermal Loop With Decentralized Plug-And-Play Heat Pumps <i>Sara Bordignon, Jacopo Vivian, Agnese Tagliaferri, Davide Quaggiotto, Michele De Carli</i>	273
The Urban-Scaled EnergyPlus Simulation Using Korean GIS to Aid Development of Energy Normalization for Shading Effect <i>Dong-Hyuk Yi, Deuk-Woo Kim</i>	281
Thermal Comfort and Environmental Impact in the Heating System Refurbishment of a Victorian Hall With Infrared Ceiling Panels <i>Roberto Rugani, Marco Picco, Fabio Fantozzi</i>	289
Personal Comfort Systems (PCSs) in Offices: Efficient Utilization Threshold Based on Energy Consumption <i>Roberto Rugani, Marco Picco, Giacomo Salvadori, Fabio Fantozzi</i>	297

Integration of Rooftop Photovoltaics and Roof Retrofitting Strategies for Enhanced Energy Efficiency in Warm Climates <i>Krithika Panicker, Prashant Anand, Abraham George, Ardeshir Mahdavi</i>	305
Effects of an Indoor Living Wall on Room Lighting Conditions: Comparison Between Measured and Simulated Data <i>Matteo Ghellere, Alice Bellazzi, Anna Devitofrancesco, Benedetta Barozzi</i>	317
Mold Growth Affecting the Achievement of NZEB in the Long Term in Tropical Climates <i>Cristina Carpino, Miguel Chen Austin, Cihan Turhan, Dafni Mora, Natale Arcuri</i>	325
Mitigating Summer Overheating of a Primary School Building Based on Dynamic Simulations <i>Ágnes Marosi, Balázs Nagy</i>	333
Analysis of Energy Consumption of a Building Placed in Milan by Adopting Common Building Insulation Materials and Recycled Surgical Masks <i>Vincenzo Ballerini, Paolo Valdiserri, Manuela Neri, Jan Kašpar, Mariagrazia Pilotelli, Edoardo Piana, Eugenia Rossi di Schio</i>	343
Recommendations to Make Reinforcement Learning Practical in Building Control Applications <i>Sourav Dey, Gregor Henze</i>	353
Simulation-based optimization for Energy- and Cost-Efficient Refurbishment of an Educational Building <i>Levente Szatmári, Balázs Nagy</i>	361
Achieving a Deeper Understanding of User-Related Influences on Artificial Lighting Energy Demand Using High-Performance Computing <i>Sascha Hammes, Johannes Weninger, Philipp Gschwandtner, Philipp Zech</i>	371
Strategic Synergy: Enhancing Building Performance Through Advanced Simulation and Shading Integration <i>Shahryar Habibi, Giovanni Pernigotto, Andrea Gasparella</i>	379
Is Solar Hydrogen a Viable Solution for Energetically Self-Sustainable Off-Grid Buildings? <i>Stefania Perrella, Roberto Bruno, Piero Bevilacqua, Daniela Cirone</i>	389
Assessment of the Simultaneity Factor Between PV Production and Electric Demand in a Real Scholar Canteen Belonging to a REC Through TRNSYS Simulations <i>Daniela Cirone, Roberto Bruno, Piero Bevilacqua, Stefania Perrella, Natale Arcuri</i>	397
Exploitation of Energy Performance Certificate Database in Urban Energy Modelling <i>Sebastiano Anselmo, Maria Ferrara, Piero Boccardo, Stefano Paolo Corgnati</i>	407
TRNSYS Dynamic Simulation Model of a Typical Air-Handling Unit: Experimental Calibration and Validation Based on Field Operation Data in the South of Italy <i>Antonio Rosato, Rita Mercuri, Mohammad El Youssef, Francesco Romanucci, Mohamed G. Ghorab</i>	415
Examining the Influence of Climatological Parameters on Building Cluster Geometry and Design Features in a Rural Indian Context: The Case of Sugganahalli Village (India) <i>Jeswin Varghese, Andrea Magdalene Pais, Suchi Priyadarshani, Monto Mani</i>	425
Estimating Indoor TVOCs in Response to Varying Humidity Regimes in Vernacular and Conventional Dwellings <i>Shreyata Khurana, Monto Mani</i>	435
Examining Indoor Humidity Ratio in Response to Varying Window-To-Wall Ratio and Ventilation in Indian Climate Zones for Earth-Plaster Based Dwellings <i>Suchi Priyadarshani, Monto Mani</i>	445
Calibrated BEMs and LSTM Neural Networks for Indoor Temperature Prediction: A Comparative Analysis in Pre- and Post-Retrofit Scenarios <i>Gianluca Maracchini, Nicola Callegaro, Rossano Albatì</i>	453
Impact of Different Radiation Decomposition Models and ERA5 Dataset on Building Energy Simulation Results: A Case Study in Brazil <i>Matheus K. Bracht, Matheus S. Geraldi, Ana Paula Melo, Roberto Lamberts</i>	461
Effects of Different Wind Speed Databases on the Performance of a Vertical Axis Micro Wind Turbine Integrated With a Typical Residential House: A Comparative Simulation Analysis for Five Italian Cities / <i>Antonio Rosato, Achille Perrotta, Luigi Maffei</i>	469
The Challenge of Archetypes Representativity for Wide Scale Building Investigation in Italy <i>Laura Carnieletto, Lorenzo Teso, Wilmer Pasut, Angelo Zarrella</i>	479

Comparison between Real Energy Consumption, Italian APE and Dynamic Energy Simulation <i>Vincenzo Pennisi, Davide Varesano</i>	487
Simulation Tests for the Determination of the U-Value of Walls by Using Response Factors Theory with Noisy Boundary Conditions <i>Maja Danovska, Davide Cassol, Ivan Giongo, Alessandro Prada</i>	495
Calibrating a Clothing Insulation Model for Thermal Comfort Assessment in Educational Buildings <i>Ilaria Pittana, Federica Morandi, Andrea Gasparella, Athanasios Tzempelikos, Francesca Cappelletti</i>	503
Alternative Affordable Solutions in Reducing the Number of Hours with Heat Strain Inside Buildings <i>Atlas Ramezani, Marco Manzan</i>	511
An Attempt to Model Ventilation Rate in Classrooms Based on the Measurement of Relative Humidity <i>Federica Morandi, Alessandro Prada, Ilaria Pittana, Francesca Cappelletti, Andrea Gasparella</i>	519
Assessment and Mapping of the Urban Heat Island Effect: A Preliminary Analysis on the Impact on Urban Morphology for the City of Turin, Italy <i>Gregorio Borelli, Ilaria Ballarini, Vincenzo Corrado, Andrea Gasparella, Giovanni Pernigotto</i>	525
Analysis of Control Strategies for Energy Performance Optimization for Educational Buildings: Comparison of Two Kindergartens in the Municipality of Bolzano, Italy <i>Angelica El Hokayem, Giovanni Pernigotto, Andrea Gasparella</i>	533
Optimization of a Solar Assisted Heat Pump System to Increase Thermal Efficiency Working on the Cold Source <i>Piero Bevilacqua, Stefania Perrella, Roberto Bruno, Daniela Cirone, Dimitrios Kaliakatos</i>	541
Simulative Applications of Novel Indicators for the Characterization and Performance Evaluation of Transparent Facades <i>Riccardo Gazzin, Giuseppe De Michele, Stefano Avesani, Giovanni Pernigotto, Andrea Gasparella</i>	549
Predicting Daylight Preferences Using HDRI and Deep Learning <i>Dongjun Mah, Athanasios Tzempelikos</i>	557
An Investigation Into Thermal Bridging Effects in an Envelope Integrated With End-Of-Life Photovoltaic Panels <i>Roshan R. Rao, Monto Mani</i>	565
Modelling Actions at the Building Stock Level for Decision-Making Towards Carbon-Neutral Cities <i>Erminia Consiglio, Luca Ferraris, Mirella Iacono, Gaetano Noé, Maria Ferrara</i>	573
A New Evaluation Framework to Assess the Prosumer Efficiency in Thermal Source District Heating Networks <i>Alireza Etemad, James O'Donnell, Alessandro Maccarini, Alireza Afshari</i>	583
The Influence of Acoustic Stressors in Educational Environments for Autistic Individuals: Preliminary Investigations <i>Marco Caniato, Federica Bettarello, Arianna Marzi, Andrea Gasparella</i>	593
Machine Learning and Data Augmentation Techniques to Cope With Solar Data Scarcity to Simulate PV Generation in Mountain Environments <i>Aleksandr Gevorgian, Giovanni Pernigotto, Andrea Gasparella</i>	601
Building Performance Simulation From Research to Professional Practice <i>Lori McElroy, Andrea Gasparella</i>	609

Assessment and Mapping of the Urban Heat Island Effect: A Preliminary Analysis on the Impact on Urban Morphology for the City of Turin, Italy

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Abstract

Urban Heat Island (UHI) effects, intensified by growing urbanization, significantly impact thermal comfort and energy demand in cities. To accurately model these effects in building performance and urban energy simulations, precise weather data and boundary conditions are essential. Although weather stations in city centers are increasingly used to develop typical meteorological years, they often fail to capture the microclimate variations across urban areas. New tools and methods are thus needed to help building professionals and municipalities assess UHI severity, use more representative weather data, and evaluate the impact of buildings on the urban microclimate. Among available tools for UHI impact assessment, Computational Fluid Dynamics (CFD) models offer detailed analysis but are computationally intensive and impractical for large-scale, year-round studies. Conversely, equivalent RC networks are more computationally efficient but still require extensive inputs, limiting their widespread use in large cities. This research introduces a new workflow using correlations to estimate UHI effects from rural weather data. The MIT Urban Weather Generator (UWG) was used to simulate UHI in representative districts, with the results employed to develop correlations for mapping local microclimates across urban areas. The proposed methodology is preliminary applied to the Italian city of Turin, focusing primarily on the correlation between urban morphology and the UHI phenomena (i.e., paying attention to those variables with the most significant effects on the local urban microclimate, according to the literature). The UHI impact has been quantified in terms of differential heating and cooling degree-days with respect to the rural environment. Results prove that with a training set of about 5 % of the city, modelled in detail with UWG,

developed correlations appear robust enough to describe the phenomenon for residential districts of Turin.

1. Introduction

The increasing urbanisation process has led to a notable intensification of the Urban Heat Island (UHI) phenomenon, which is affecting both indoor and outdoor thermal comfort, as well as the energy demand of neighbourhoods and cities (Li et al., 2019). This phenomenon is driven by several factors, including urban morphology, material albedos, anthropogenic heat, and the lack of evapotranspiration due to the absence or limited presence of vegetation. The interaction of these factors, along with their spatial variability within urban contexts, results in a multitude of microclimates within urban areas.

In this context, the use of representative weather data and boundary conditions must be considered to increase the accuracy of the simulation at building and district scale. In the past, weather data were typically obtained from rural areas or external locations such as airports. Nevertheless, data from urban locations have been recently incorporated in building simulations towards a more accurate definition of climatic conditions. However, this solution is not able to entirely capture the microclimate variability within a city. For this reasons, different tools have been developed to assist policymakers in mapping the UHI and formulate mitigation strategies. These tools can be classified in two different categories: Urban Energy Balance (UEB) models and Computational Fluid Dynamics (CFD) models. CFD

models, as ENVI-MET (Bruse & Fleer, 1998), solve the governing equations of fluid motion, allowing for high spatial resolution and precision. However, they necessitate substantial simulation and computational time, as well as advanced expertise and knowledge for model definition. Consequently, CFD applications at the district scale are typically confined to selected case studies over specific periods of the year. In contrast, UEB models use urban metrics to simplify and accelerate the description and calculation of the urban energy balance. The most used and spread tool in this category is the Urban Weather Generator (UWG) (Bueno et al., 2013). The UWG is an RC (resistance-capacitance) model comprising four sub-models: the Rural Station Model (RSM), the Vertical Diffusion Model (VDM), the Urban Boundary-Layer Model (UBL), and the Urban Canopy and Building Energy Model (UC-BEM). This model provides air temperature and humidity data for urban contexts starting from a rural weather data. The advantages of UEB models like the UWG include a faster computational speed compared to CFD models and the ability to generate weather data with UHI effects that can be directly used in urban and building simulation tools. Additionally, these models require less data and expertise for their definition.

However, UHI mapping and weather files still require a significant amount of data to cover both local and entire urban areas. Among the several factors that influence both simulations and real-world scenarios, urban layout has the most significant impact (Salvati et al., 2019). Urban geometry can vary significantly between cities and urban areas, making the definition of representative districts a powerful way to reduce data needs and extend analysis to the entire city. Different methods exist for clustering urban layouts. Among them, the most widely used is the Local Climate Zone (LCZ) classification (Stewart & Oke, 2012). However, other techniques and workflow have been developed to improve the LCZ classification, usually characterized by excessively broad classes. These alternative procedures, such as the one proposed by Joshi et al. (2022) or Boccalatte et al. (2023), integrate additional urban metrics and clustering techniques to obtain more representative districts archetypes that can be used for climate analysis.

Considering this context, a novel workflow is proposed in this study in order to map the UHI and weather data in the cities by the definition of representative district. The proposed methodology is preliminary tested on a case study, considering only urban morphology metrics for the definition of representative districts.

2. Methods

This paper presents a methodology to map the UHI and urban climate. The workflow (Figure 1) is structured in five steps: i) Metrics calculation, ii) Cases selection, iii) Microclimate simulation, iv) Correlation and validation and v) Mapping.

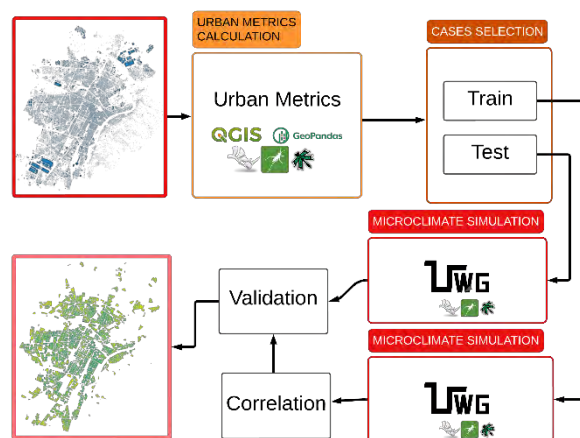


Fig. 1 – Methodology scheme

The main scope of this preliminary analysis is to assess possible correlations between urban parameters and microclimate metrics. To that purpose, different cases are selected according to the urban metrics. The microclimate effect is acknowledged to be significant at neighbourhoods' level. Therefore, the buildings in the city are grouped into urban blocks by clustering all the buildings with adjacent parcels area. The blocks with fewer buildings, irregular shape, or large area (mainly composed by industrial area and factory) are no object of the analysis and so were removed. For each filtered block, 10 urban metrics (Table 1) are defined among the most used metrics in literature (Javanroodi et al., 2023) and among the ones used by Joshi et al. (2022).

Table 1 – Urban Metrics

Metrics	Formula
Floor Area Ratio (FAR)	$FAR = \frac{\sum A_i * n_i}{A_{block}}$
Volume Area Ratio (VAR)	$VAR = \frac{\sum V_i}{A_{block}}$
Relative Compactness (REC)	$REC = \frac{\sum \frac{6V_i^2}{A_{i_frontal}}}{n}$
Shape Factor (SF)	$SF = \frac{A_{block}}{\pi r_{min\text{bounding}}^2}$
Surface Coverage (SC)	$SC = \frac{\sum A_i}{A_{block}}$
Green Ratio (GR)	$GR = \frac{A_{veg}}{A_{block}}$
Average Building Height (ABH)	$ABH = \frac{\sum h_i}{n}$
Sky View Factor (SVF)	<i>Qgis plugin</i>
Average Building Distance (ABD)	$ABD = \frac{\sum d_i}{n^2}$
Vertical to Horizontal (VtH)	$Vth = \frac{\sum A_{vert}}{A_{block}}$

The metrics calculation process requires different software, such as QGIS and Rhinoceros, and python libraries, such as Geopandas. The Sky View Factor (SVF) is calculated using the QGIS plug in Relief Visualization Toolbox (Zakšek et al., 2011) that requires a digital surface model (DSM) as input data and produces the same raster vector with the calculated metrics. From the image raster the SVF for the building block is calculated as the average value on a virtual block positioned at half of the minimum distance to the closest block. This results in assigning to each building block the SVF value that corresponds to the one calculated in the middle of the streets. This approach is used in order to take into account the surrounding street canyon.

To proper select the urban metrics, a Spearman correlation analysis is performed to consider more independent metrics and sample the blocks population. The main statistical values for the selected metrics (e.g., Q_1 , median, Q_3) are combined to define a

representative population of districts. The blocks with the closest morphological features to each combination are selected as train subset for the correlation definition. The cases selected are modelled and simulated with the Urban Weather Generator (UWG) to create the urban weather file and data of interest (e.g., Heating Degree Days HDD, Cooling Degree Days CDD, Mean temperature, UHI index). On the selected outcome, different techniques can be adopted and implemented in order to correlate the input variable with the climate metrics and weather data.

The defined correlations are tested and verified on the result of an urban block subset randomly chosen. The outcome of the validation process gives information concerning the possibility to extend the metrics to all the city mapping and extracting information.

3. Case Study

The methodology proposed is tested and applied to the city of Turin, which has an estimated population of 848,000. The data used in this study is provided by the Municipality of Turin and includes a GIS model of the city and a digital surface model (DSM) input for the SVF calculation. The city is composed of 128,144 buildings, which are grouped into 4,518 blocks based on their cadastral parcel area. The filtering criteria are selected as follows: each block must have (1) a minimum of four buildings, (2) a SF higher than 0.1, and (3) an area lower than 0.1 km². Those criteria allow for the removal of uncommon blocks geometry, single or few building blocks, as well as removing huge industrial area in outside parts of the city. The final population is composed of 2,804 blocks. All the metrics selected are then calculated. The results of the correlation analysis using the Spearman method are reported in Table 2.

According to the results, the variables selected for the analysis and significant to the representative blocks definition are: i) Green ratio, ii) Surface coverage, iii) Average building height, iv) Vertical to horizontal, which are reported in Figure 2.

Table 2 - Spearman correlation

SF	1	-0.095	-0.037	0.059	0.063	0.058	0.064	-0.023	-0.21	0.24
SVF	-0.095	1	0.2	-0.17	-0.25	-0.26	-0.29	0.32	0.27	-0.34
GR	-0.037	0.2	1	-0.37	-0.099	-0.27	-0.3	0.13	0.5	-0.34
SC	0.059	-0.17	-0.37	1	0.08	0.54	0.61	0.013	-0.032	0.19
Abh	0.063	-0.25	-0.099	0.08	1	0.6	0.73	-0.71	-0.084	0.61
FAR	0.058	-0.26	-0.27	0.54	0.6	1	0.85	-0.4	-0.16	0.63
VAR	0.064	-0.29	-0.3	0.61	0.73	0.85	1	-0.51	-0.13	0.64
REC	-0.023	0.32	0.13	0.013	-0.71	-0.4	-0.51	1	0.22	-0.53
Abd	-0.21	0.27	0.5	-0.032	-0.084	-0.16	-0.13	0.22	1	-0.59
Vth	0.24	-0.34	-0.34	0.19	0.61	0.63	0.64	-0.53	-0.59	1
	SF	SVF	GR	SC	Abh	FAR	VAR	REC	Abd	Vth

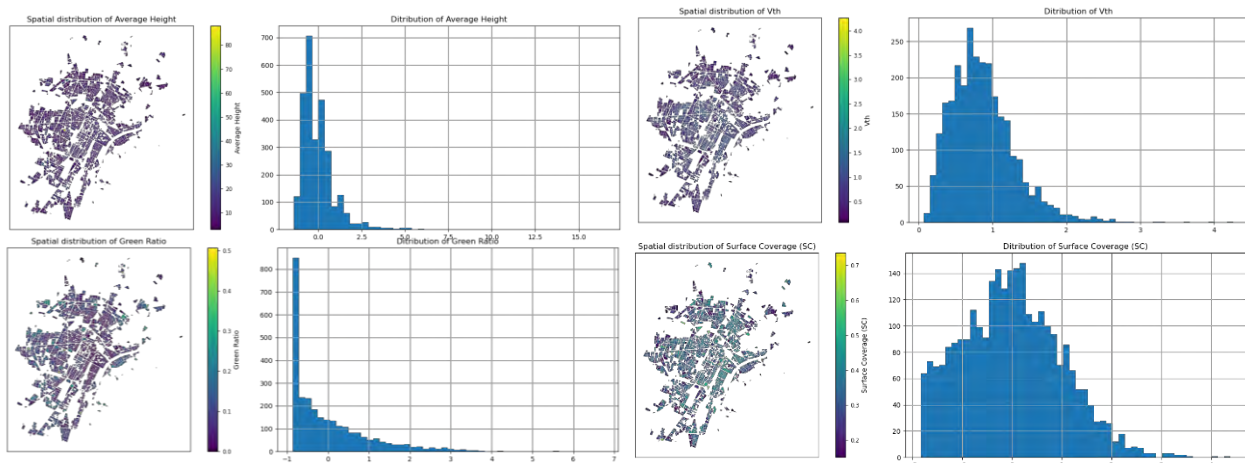


Fig. 2 – Distribution of metrics selected

The relevant statistical points, combined for the representative cases, are the minimum, the 10th percentile, Q_1 , median, Q_3 , the 90th percentile, and maximum value of the distribution. This approach ensures a complete spatial sample, including the extreme cases. The total train sample, after removing duplicates, is composed of 171 blocks, which represent 6 % of the total sample. The blocks, shown in Figure 3, are uniformly distributed across the city. The test sample is composed of 20 cases chosen randomly (Figure 3).

The geometry property of the selected blocks is employed as input for the UWG, combined with the vegetation information present in GIS data. The other parameters (e.g., the anthropic heat and building archetype) are taken as default values, given the

morphological aspect focus of this preliminary analysis. Due to their strong correlation with the building energy demand, the selected metrics are the Heating and the Cooling Degree Days variations between the simulated values and the ones resulting from the rural weather station (TORINO 160590 IWEC), characterized by CDD_{18} equal to 381 K d and HHD_{18} equal to 2505 K d. As a first trial, a simple linear correlation is performed on both the metrics investigated.



Fig. 3 – Spatial disposition of Train sample (Blue) and Test sample (Green)

4. Results

The linear correlation carried out on the datasets provides a positive outcome for both the metrics. The cooling degree days correlation is reported in Figure 4.

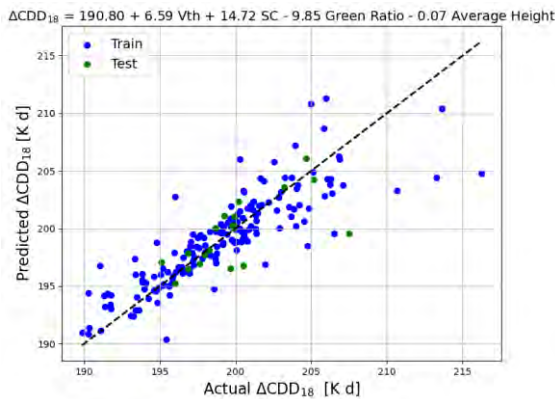


Fig. 4 – Cooling degree-days correlation

The trained sample shows a good correlation, as confirmed by a R^2 value of 0.73 and a RMSE value of 2.39 K d. On the test sample, an RMSE value 2.31 K d is considered acceptable for the validation of the correlation, being lower than the RMSE of the training sample. Among the different metrics, the vertical to horizontal (Vth) is the one with the biggest

influence, followed by the surface coverage (SC) and green ratio (GR), which has a counter effect on the CDD variation. The average building height shows a very low impact. Similar results for the heating degree days correlation are reported in Figure 5, with a R^2 of 0.74 a RSME on the train sample of 4.98 K d. The RMSE of 4.63 K d on the test sample is higher than the one found for the Cooling Degree Days analysis but again acceptable for the validation purpose. The trends for the different variables are similar in absolute value and opposite in sign compared to the Cooling Degree Day.

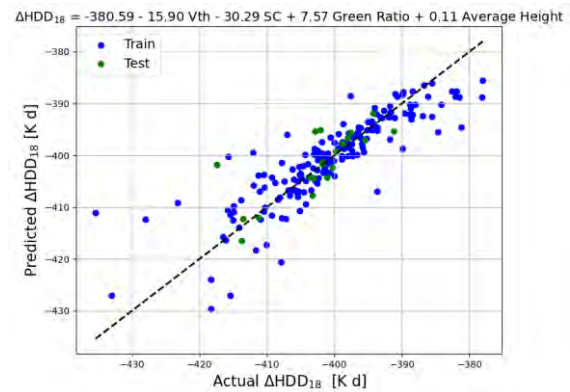


Fig. 5 – Heating degree-days correlation

These correlations allow us to map the metrics variation inside the cities, as shown in Figures 6 and 7. The average variation of the metrics inside the cities are -402 K d for the Heating Degree Days, corresponding to a reduction of 16 %, and a significative increase of 200 K d (+52 %) for Cooling Degree Days. The variation range inside the different blocks configurations is 66 K d for the HDD that correspond to the 3 % of the average urban HDD value. More important is the variation range of the CDD. It corresponds to 30 K d, resulting in 5 % of the average CDD value inside the urban area.

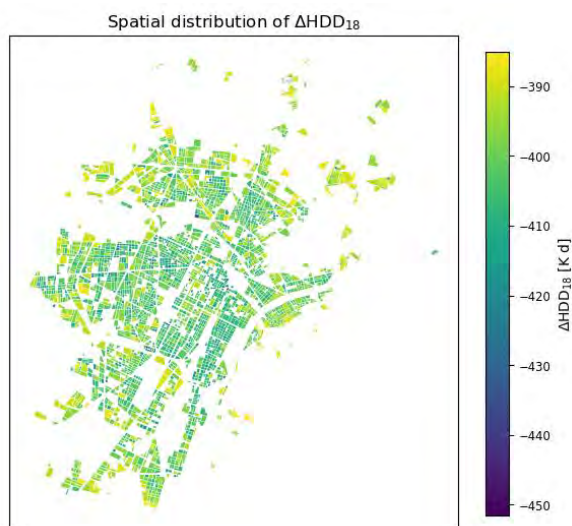


Fig. 6 – Heating degree days spatial distribution

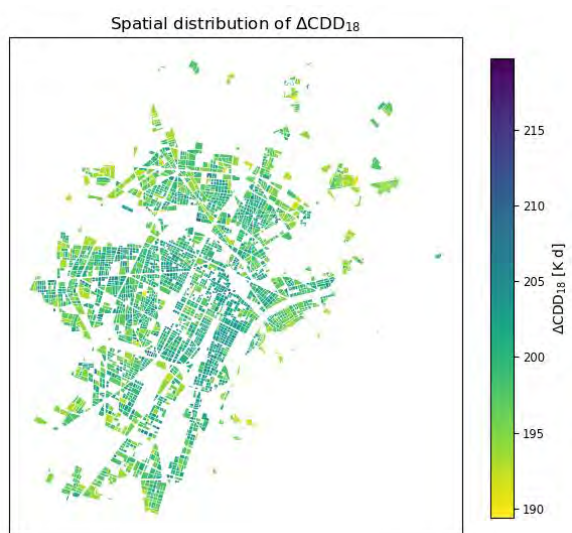


Fig. 7 – Cooling degree days spatial distribution

5. Conclusion

This study introduces a novel methodology for mapping urban microclimates and establishing boundary conditions for urban and building simulations. The approach adopted emphasises the identification of correlations between environmental variables and urban morphological metrics, thereby reducing the computational time and data requirements by a significant extent. By calculating a range of metrics within an urban context, a small, representative subset of districts is identified for the purpose of training the correlation model.

Subsequently, the selected districts are modelled using the Urban Weather Generator (UWG) to produce urban microclimate data and extract urban heat island (UHI) metrics based on the established correlations. The methodology is initially evaluated in the case study of Turin, with a primary focus on morphological parameters. By simulating a mere 6 % of the total urban blocks, a clear correlation is identified between urban metrics and variations in Heating Degree Days (HDD) and Cooling Degree Days (CDD) in comparison to a rural climate baseline.

The results demonstrate the considerable impact of urban morphology on climate variations, with vertical-to-horizontal metrics and surface coverage identified as the most influential factors. Furthermore, the study demonstrates that the mean discrepancy in HDD and CDD is considerable, with CDD exhibiting notable disparities across diverse urban zones. The results validate the effectiveness of the proposed methodology in mapping urban heat islands using urban metrics, reducing both the data requirements and the computational time.

The workflow is adaptable and can be readily applied to other contexts and metrics. However, the principal limitation of this approach is its narrow focus on urban morphology, without accounting for other crucial factors such as anthropogenic heat, building archetypes, and wind patterns. Future research should seek to incorporate these additional variables and conduct a real case validation to enhance the precision and applicability of the methodology.

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