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Urban-Scale Energy Models: the relationship between cooling energy demand and urban form

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Abstract. To enhance the quality of life in cities, it is necessary to improve the energy performance of buildings together with a sustainable urban planning especially in high-density contexts. Previous works investigated the building shape, the urban morphology, and the local climate conditions to optimize the energy performance for space heating of buildings. The aim of this study is to validate a GIS-based engineering model to simulate the hourly energy demand for space cooling in residential buildings at neighborhood scale and to assess the relationship between the urban form and the energy performance in terms of cooling energy demand. A place-based methodology was applied to six neighborhoods in the city of Turin (Italy), identified as homogeneous zones with different building characteristics and urban contexts. The hourly cooling demand of residential buildings was studied starting from the energy balance at building scale, and then was applied at block of buildings scale with the support of GIS. This model was validated with a comparison of the results using CitySim tool and ISO 52016 assessment. In order to investigate the relationship between cooling energy demand and urban form, the GIS-based engineering model was applied to five typical blocks of buildings with different construction periods. The results show how cooling energy demand varies according to building characteristics and urban morphology in a continental-temperate climate. By this analysis, it is possible to identify the optimal block of building shape in Turin ensuring lower energy consumptions during the cooling season with different types of buildings.

Key Words: urban-scale energy model, hourly energy simulation, engineering model, cooling energy demand, urban form, residential buildings.

1. Introduction

A growing number of countries and cities is setting targets for the reduction of greenhouse gas (GHG) emissions and for the mitigation of climate changes [1]. The Clean Energy for all European Package encourages all state members to increase energy efficiency and the use of renewable energy sources (RES) to promote sustainable development, especially for the buildings sector. Reducing the energy consumption of buildings is one of the main goals of European policies, in order to increase the livability and sustainability in urban areas [1], [2]. Especially in these contexts, an increase in energy demand for cooling is expected [3]. Analysis on the energy consumption of buildings at urban scale can support the identification of proper energy urban planning for both the design of new neighborhoods and the priority of retrofit interventions on existing building stock. The development of urban-scale energy models (USEMs) is an actual and very broad research field: a variety of energy models allows to assess the energy performance of buildings taking into account the relationships between the buildings and the surrounding environment [4]. The main characteristics of USEMs are: the approach used (top-down, bottom-up and engineering), the accuracy of input data, the time requested to process data and the possibility to integrate and manage variables at different scale [5]. USEMs are able to assess energy consumption at multiple temporal (hourly, daily, monthly and annual) and spatial scales (from building, neighborhood, district to urban scale). The GIS tools utilize existing databases (normally used for urban development plans), manage energy-related variables to identify GIS-based energy models, and provide the possibility to visualize spatiotemporal results [6].

1.1. Research background

Built environment and local climate conditions of urban areas influence energy performances of buildings [7], [8]. The high presence of anthropogenic heat sources and the scarcity of green areas increase the urban heat island (UHI) effects [9]. Urban morphology can modifies solar access, wind speed and direction, affecting buildings' energy performances [8]; it can occur in a negative or in a positive manner, according to heating or cooling season, generally compensating one the other. Studies have shown that more compact urban environment results in lower thermal losses, providing for a decrease in the heating energy demand suitable in cold climates. In contrast, in hot climate high built density has been associated with an increase in cooling energy consumption due to the reduction of wind speed and higher air temperatures. In the same way, wider street canyons provide better wind conditions at the expenses of an increase in solar radiation exposure of building façade that can affect the solar gains both on the opaque envelope and transparent components.

Tools and models have been developed to estimate building energy consumption at city scale, the most used are: CitySim, UMI, Simstadt, CityBES and open formats as CityGML. This one ensures the availability, quality and accessibility of spatial information, as expected by the INSPIRE EU Directive 2007/2/EC. Since the relationship between buildings and urban form influences the energy consumption, the urban environment needs to be described considering all energy-related parameters. The urban parameters that are mainly used to describe the urban morphology are: *building coverage ratio* (*BCR*, m^2/m^2), *building density* (*BD*, m^3/m^2), *main orientation of the streets and buildings* (*MOS*, -), *aspect ratio* or *height-to-width* ratio (*H/W*, m/m), *sky view factor* (*SVF*, -), *green area ratio (GAR,* m^2/m^2*)* and *normalized difference vegetation index* (*NDVI*, -) [5], [10], [11], [12].

1.2. Research objectives

The main purpose of this work is to validate a GIS-based engineering model to simulate the hourly energy demand for space cooling of residential buildings at neighborhood scale, as it was already validated for space heating energy demand [5]. Differently from models that need ad hoc databases, this simplified model uses existing open databases, normally utilized by urban planners. It elaborates these data with a GIS-based assessment to evaluate energy consumptions with spatial information and low times simulation, calculating and adapting some of the input variables from building to block of building scale. In addition, this work investigates the relationship between urban form and the energy performance of typical blocks of buildings during the summer season, to understand the effect of buildings typology and urban morphology on cooling energy demand.

2. Materials and Method

This section describes energy models and tools used to simulate cooling energy demand, the input data and the case study. The hourly cooling energy demand of residential buildings was simulated for six different neighborhoods in the city of Turin (Italy).

In the first part of this work, the GIS-based engineering model has been fixed up and then validated at urban scale by comparing the cooling demand simulated at two scales: (i) at building scale, considering five typical residential buildings for each of the six neighborhoods (30 buildings), and the comparison has been carried out with CitySim tool and ISO 52016 standard assessment; (ii) at block of buildings scale, five blocks of buildings with different urban shapes have been selected among the neighborhoods, and the simulations have been carried out with CitySim tool.

In the second part, the GIS-based engineering model has been applied to the five different blocks of buildings in order to evaluate how the urban form influences the demand for space cooling considering also different types of buildings as a function of the relative construction periods (until 1918, 1961-70, 1981-90, and after 2006).

2.1. Urban-scale energy models and tools

According to previous works [2], [5], an existing GIS-based engineering model has been designed and validated for the space heating simulations at urban scale. In this study, the same model was improved to evaluate hourly cooling energy demand of residential buildings at building level and at block of buildings scale comparing its results with: CitySim tool [13] and the assessment of ISO 52016-1:2017. To design the GIS-based engineering model, the dynamic building thermal balance (according to ISO 52016-1:2017 and ISO 52017:2017 standards) was adapted to the neighborhood scale using GIS tools and the information of buildings from the municipal technical map. The GIS-based model is a lumped parameter model based on three thermodynamic systems (TSs): (i) the opaque envelope, composed by all opaque surfaces that separate the heated volume of the buildings from the external environment (or unheated zones); (ii) the glazing component, that separates the heated zone from the external environment; (iii) the inside part of the building which include internal partition and structures, air, occupants, and furniture. Equation 1 describes the dynamic heat balance for each TS ($\emptyset_T$ and $\emptyset_V$ are positive when the external temperature is minor than the internal one) and Figure 1 the application at block of building scale.

$$C_{TS}\frac{dT_{TS}}{dt} = \emptyset_{sol} + \emptyset_I - (\emptyset_C + \emptyset_T + \emptyset_V) \quad (1)$$

where, for each TS: C is the heat capacity (JK^{-1}); T is the temperature of the TSs (K); t is the time (s); $\emptyset_{sol}$ is the heat flow rate from solar gains; $\emptyset_I$ is the heat flow rate from internal gains; $\emptyset_C$ is the heat flow rate from the cooling system; $\emptyset_T$ is the heat flow rate by transmission; $\emptyset_V$ is the heat flow rate by ventilation (usually in Italian residential buildings, the humidification and dehumidification of air is not controlled, then only sensible heat flow components were considered).

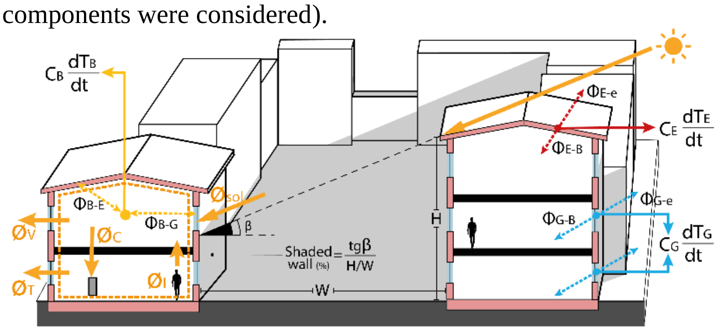


Figure 1. TSs of building (B), opaque envelope (E), and glazing (G) at block of buildings scale.

To describe the urban morphology and the buildings geometry, GIS tools have been applied to the built environment at district scale; in particular ArcGIS 10.7 and SOLWEIG 4.2 have been used to calculate the built areas, volumes, *SVF* at ground-roof level and *H/W* to characterize solar exposition and shadows. The novelty of this model is the application of the heat balance of buildings at the neighborhoods adapting some variables from the building scale to the district scale. In particular, two urban parameters (*SVF* and *H/W*) –that allow to include mutual shading and view factors of surrounding built-up context– were used to evaluate heat fluxes between the block of heated-cooled buildings and the external environment at a neighborhood scale [2]. Input data were processed and elaborated with the support of GIS tools [2,5]; the main information refer to: (i) geometrical characteristics of the buildings, such as the surface-to-volume ratio (*S/V*), the heat loss surfaces, the glazing area (that was assumed as 1/8 of the net floor area, Italian Decree 190/1975), and the heated net volume (75% of the gross volume); (ii) thermo-physical properties of the buildings according to the relative construction period: thermal transmittances (*U*) and thermal capacities (*C*) of opaque and transparent envelope, and solar energy transmittance of the glass ($g_\perp$); (iii) local climate conditions refer to climate data recorded by the nearest weather station.

For the cooling demand simulation, firstly, the urban building thermal balance was applied at building scale in order to calibrate the model; secondly the input data were aggregated at block of buildings scale and the GIS-based engineering model was validated at this scale. Thanks to the flexibility of the methodology, the model can be quickly applied to different scales. The presented model is able to guarantee an accurate urban-scale results with less input data and the model simulation times are significantly lower than existing tools [5].

2.2. Case study

A place-based methodology was applied to six neighborhoods in the city of Turin (Italy), identified as homogeneous zones with different building characteristics and urban contexts [14]. In the city of Turin, the quota of residential buildings is around the 75% of the heated building stock, and the 80% of them was built before the 1970 (before the first Italian Law on energy savings in buildings). In this work the model was applied taking into account the construction period as a reference to identify different thermo-physical properties of the buildings, since the real energy consumption data for space cooling were not available. Table 1 shows the thermal transmittances (W/m^2/K) and the thermal capacities (kJ/m^2/K) of the opaque and transparent building components for nine construction periods used as input data.

Table 1. Thermo-physical properties of the buildings

Period	U_g	U_{wall}	U_{roof}	U_{floor}	$g_\perp$	$C_{envelope}$
	W/m²/K				-	***kJ/m²/K***
< 1918	5.9	1.45	1.8	1.75	0.82	504
1919-45	5.9	1.35	1.8	1.58	0.82	504
1946-60	5.9	1.18	1.8	1.23	0.82	283
1961-70	5.9	1.13	2.2	1.3	0.82	283
1971-80	5.9	1.04	2.2	1.21	0.82	257
1981-90	3.3	0.78	1.18	1.95	0.70	264
1991-00	2.7	0.7	0.68	0.8	0.70	274
2001-05	2.7	0.7	0.68	0.8	0.70	274
> 2006	1.8	0.46*	0.43*	0.43*	0.62	267

*Legislative Decree 311, 29 December 2006

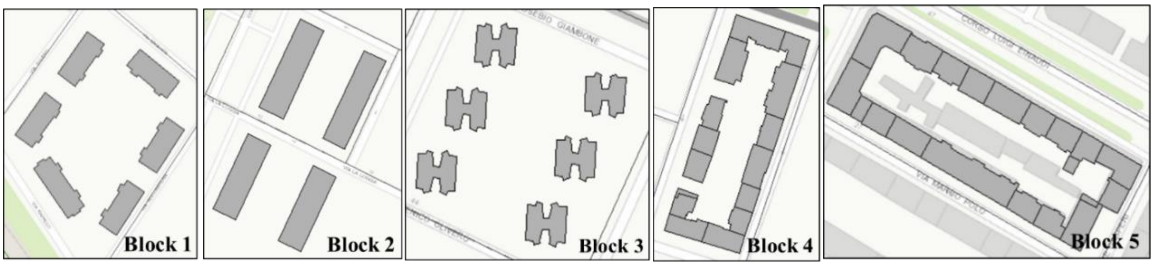


Figure 2. Blocks of buildings.

Table 2. Blocks of buildings' characteristics

Block of Buildings		**Block 1**	**Block 2**	**Block 3**	**Block 4**	**Block 5**
Neighborhood (name)		**Arquata**	**Villaggio Olimpico**		**Mediterraneo**	**Crocetta**
N. of buildings	-	6	4	6	15	20
Surface of flat	m^2/flat	62	114	90	79	117
Components per family	Inh/fam	1.63	2.16	2.09	1.85	2.05
Prevalent Period	-	1961 - 1970	1971 - 1980	1961 - 1970	1946 - 1960	1961 - 1970
U_{wall}	W/m^2/K	1.13	0.93	1.13	1.16	1.2
U_{roof}		2.2	1.73	2.2	1.73	2.02
U_{floor}		1.3	1.55	1.3	1.20	1.40
$U_{glazing}$		5.9	4.72	5.9	5.74	5.9
$g_\perp$	-	0.82	0.77	0.82	0.81	0.82
$C_{envelope}$	J/m^2/K	282,518	260,199	282,518	282,094	345,277
Window-to-wall ratio	%	14	20	12	21	23
S/V	m^2/m^3	0.41	0.29	0.38	0.28	0.27
Prevalent Azimut	°	N/W = +125	N/W = +155	N/W = +165	N/W = +110	N/E = -150
		S/E = -55	S/E = -65	S/E = -85	S/E = -70	S/W = +30
BCR	m^2/m^2	0.16	0.31	0.12	0.31	0.38
BD	m^3/m^2	2.58	7.99	3.88	8.63	7.78
H/W	m^2/m^2	0.22	0.35	0.37	0.73	0.58
SVF	-	0.77	0.74	0.82	0.68	0.67

The GIS-based engineering model has been calibrated and validated at urban scale by comparing the cooling demand simulated at a block of buildings scale. Figure 2 shows the five blocks of buildings selected. It is possible to observe different urban form: open-court buildings-Block 1, row-Block 2, tower-Block 3, courtyard-Block 4-5); blocks 4 and 5 represent the typical courtyards in the city of Turin with high-building density and different orientations. The main input data at block of buildings scale are reported in Table 2; the variables in the last rows well describe the different urban forms.
Energy simulations have been done according to the cooling season 2014 (same year used for the previous work [2]). Since in Turin the cooling energy consumptions is quite low, to analyze the results of the GIS-based model in the summer season, the warmer day of each month has been chosen: May 30th, June 12th, July 18th, August 5th and September 1st. In Table 3 the average ($T_{ae,avg}$) and maximum daily ($T_{ae,max}$) air temperature (°C), and the global horizontal irradiation (*GHI*, kWh/m^2) have been indicated.

Table 3. The warmer day of each month for the cooling season 2014.

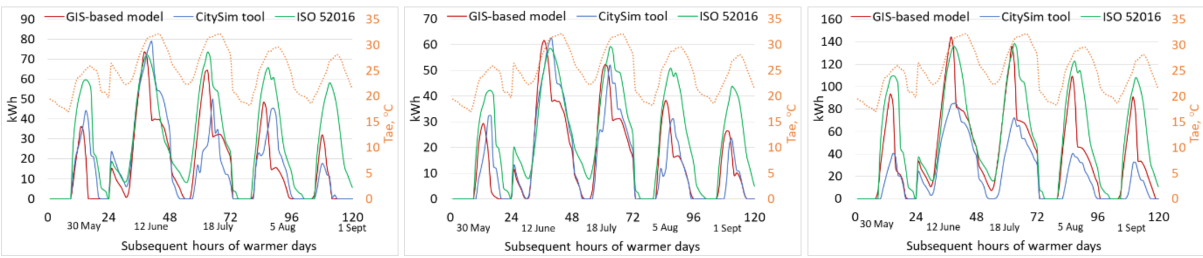
	May 30th	**June 12th**	**July 18th**	**August 5th**	**September 1st**
$T_{ae,avg}$,°C	21.4	28.7	27.6	24.3	23.0
$T_{ae,max}$,°C (hour)	25.9 (4 p.m.)	33.6 (5 p.m.)	32.1 (7 p.m.)	29.6 (6 p.m.)	28.1 (5 p.m.)
GHI, kWh/m^2/day	6.91	7.36	6.98	7.08	6.23

3. Results and Discussion

This section presents the GIS-based engineering model calibration and validation by analyzing the monthly, daily and hourly results. The cooling energy demand of 30 typical buildings for each neighborhood has been simulated for the summer season 2014 comparing the GIS-based engineering model outputs to CitySim tool and ISO 52016 standard. Afterwards, the effect of urban forms on cooling energy performance has been investigated using the GIS-based engineering model according to four different periods of construction.

3.1. GIS-based engineering model validation

The results of the hourly simulation of three residential buildings are shown in Figure 3: 'ED-5' built in 1919-46 in Crocetta neighborhood; 'ED-2' built in 1946-60 in Mediterraneo neighborhood; and 'ED-3' built in 1981-90 in Villaggio Olimpico neighborhood. The hourly cooling energy profiles assessed with the GIS-based model (in red), the CitySim tool (in blue) and the ISO 52016 standard (in green) are compared.

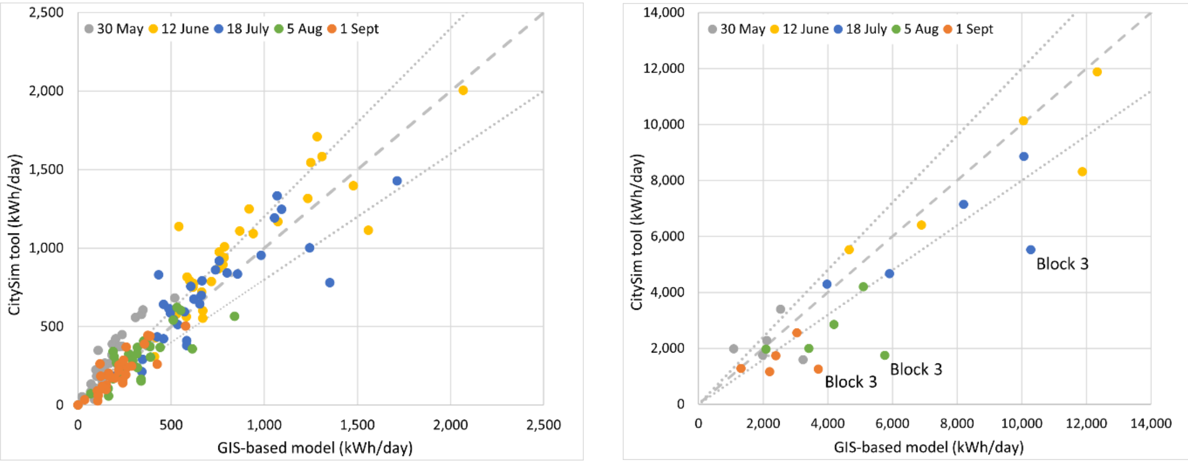


(a) 'ED-5' (1919-46, NW-SE) (b) 'ED-2' (1946-60, E-W) (b) 'ED-3' (1981-90, NE-SW)

Figure 3. Crocetta neighborhood: comparison of hourly cooling demand for the five warmer days: GIS-based model, CitySim tool and hourly method ISO 52016.

It can be observed that the hourly energy profiles have a typical trend related to the external air temperature T_{ae} (and to the solar irradiation). The GIS-based model and the CitySim tool results are very similar: the hourly energy peaks for the five days, and for both buildings are very close. The ISO 52016 standard simulates higher consumption than the other two tools, especially for month with lower external air temperature (May and September). These differences are mainly due to the fact that local climate conditions refer to the typical meteorological year (not to 2014); in this case, correlations between air

temperature/global horizontal irradiance and cooling demand have been used to compare the results according to the weather data used in the CitySim tool and the GIS-based engineering model.
The annual absolute relative error for the cooling season (April 15th - October 15th) calculated at building level is on average 30% (median 26%). There were minimum values of 21 and 22%, respectively in Raffaello and Crocetta neighbourhoods, and a maximum value of 70% in Villaggio Olimpico neighbourhoods. These results are compatible with the application of the GIS-based model which is on an urban scale and not on a building scale. The precision of the GIS-based model depends on the urban form, and it has been designed for the typical district of the city of Turin, the courtyard. Raffaello and Crocetta represent the typical neighbourhood of the city with compact condominiums built between 1946 and 1980, while Villaggio Olimpico was built more recently and it is characterized by towers and big isolated condominiums. It is necessary to consider that the relative error has less meaning when it refers to very low energy demands such as 2 to 6 kWh/m^3/year.



(a) Building scale: 30 buildings (b) Block of buildings scale: 5 blocks

Figure 4. Comparison of daily cooling demand for the five warmer days: GIS-based model and CitySim tool at building (a) and block of building scale (b).

Figure 4 shows the comparison of the daily cooling demand between the GIS-based model and the CitySim tool calculated for the five warmer days. In Figure 4a, the results refer to the energy simulations of the 30 residential buildings analyzed, while Figure 4b reports the cooling energy demand calculated for the five blocks of buildings. The GIS-based model shows a good accuracy in both cases, especially in June 12th and July 18th thanks to the highest daily temperatures, 33.6 and 32.1 °C, respectively.

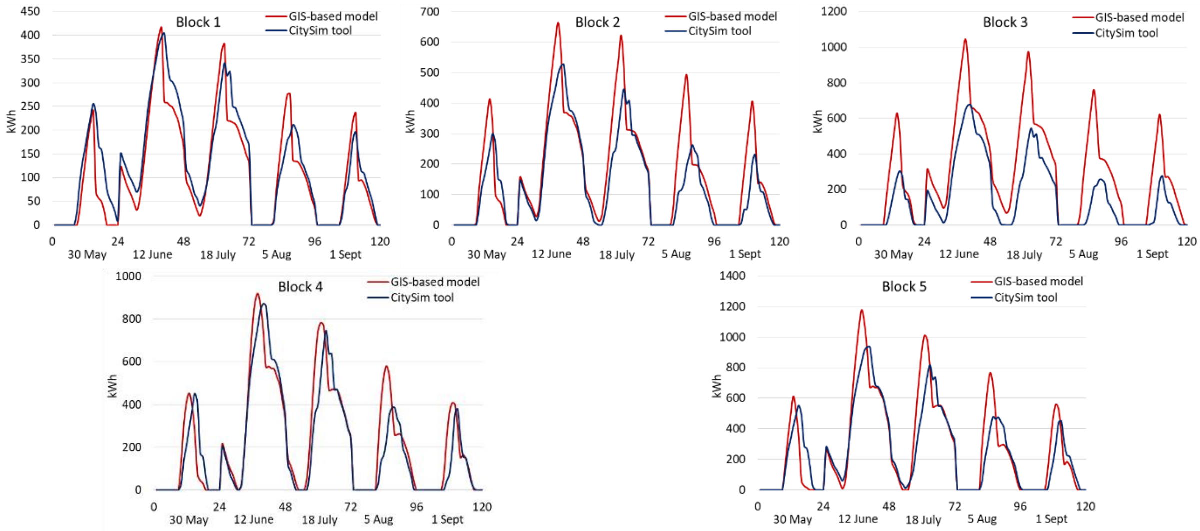


Figure 5. Comparison of hourly cooling demand at block of buildings scale for the five warmer days: GIS-based model and CitySim tool.

Figure 5 shows the comparison of the hourly space cooling demand between the GIS-based model (in red) and the CitySim tool (in blue) calculated for the five warmer days at block of buildings scale. As already observed in Figures 3 and 4, the model is less accurate for Villaggio Olimpico block 2 and especially for block 3. The precision also depends on the number of buildings in each blocks and on the scale of application [15], this is another reason why the GIS model is more accurate in blocks 4 and 5 with 15-20 buildings, compared to blocks 2 and 3 with 4-6 isolated buildings.

3.2. The effect of urban form on cooling demand

In this section the effect of urban form on cooling energy demand has been analysed by investigating the energy performance of five blocks of buildings (in Figure 2). This analysis takes into account different thermo-physical properties according to four construction periods: until 1918, 1961-70, 1980-90, and after 2006. The four construction periods have been selected considering a consistency variation of the thermal transmittance values of the opaque and transparent components and of the thermal capacities of the envelope that characterizes the buildings.

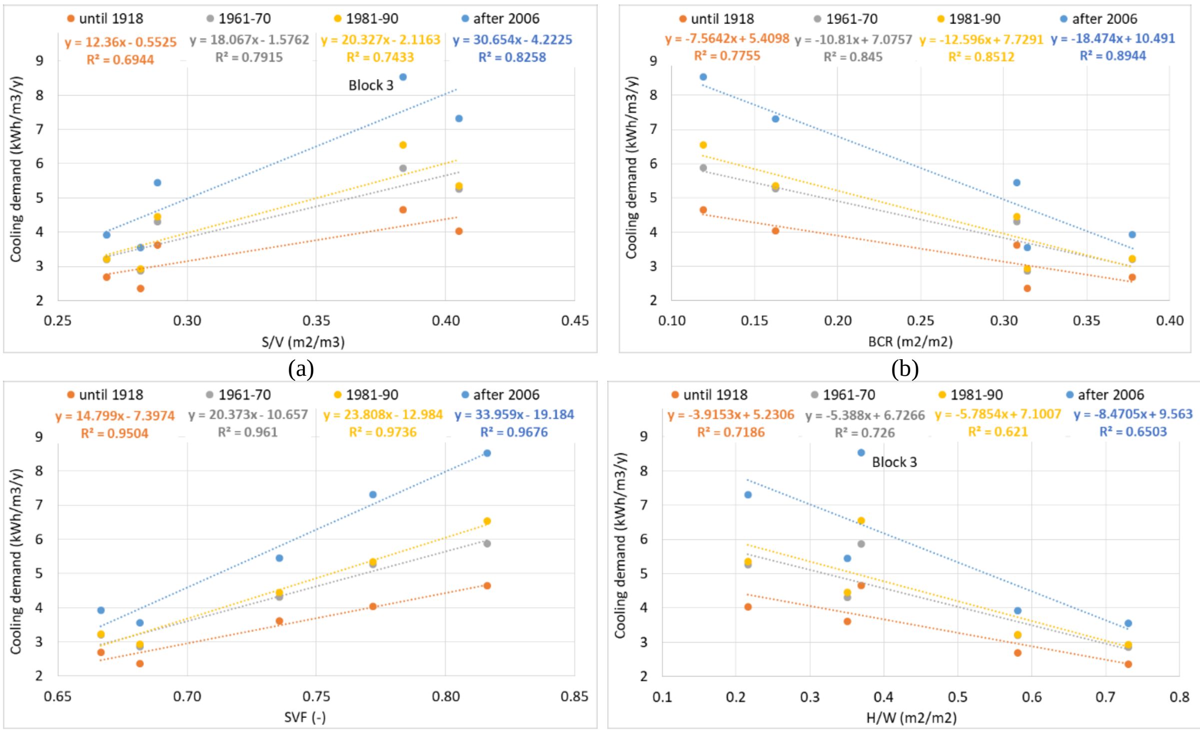


Figure 6. Simulation at block of buildings scale using the GIS-based engineering model for different urban forms and construction periods: correlation between the cooling demand and (a) the surface-to-volume ratio (*S/V*), (b) the building coverage ratio (*BCR*), (c) the sky view factor (*SVF*), and (d) the height-to-width ratio (*H/W*).

The main findings (in Figure 6) can be summarised as follows: (i) in all blocks of buildings investigated, older buildings have lower cooling energy demand, probably due to the higher thermal capacity values; (ii) cooling energy demand increases as *S/V* and *SVF* increase, and decreases with high values of *H/W* and *BCR*; (iii) the courtyard block (typical urban form in historical Turin districts), and the South-North orientation (block 4 in Mediterraneo) has the lowest cooling demand; (iv) the towers, behave abnormally and the GIS model is not accurate with this urban shape (block 3 in Villaggio Olimpico).

4. Conclusion

This work investigates how the urban form affects the energy performance of residential buildings during the cooling season. A GIS-based engineering model have been firstly validated for district-scale

applications, and then used to simulate the cooling energy demand in different neighborhoods with various morphologies.
This model uses urban variables mainly to evaluate the solar fluxes and the extra flux to the sky at block-scale. Thus, at the building scale the accuracy is low, but at the block scale it works with the exception of the isolated towers in block 3; the model has an accuracy that seems proportional to the number of buildings in the district. From the results it has emerged that the urban form and the shape of the built environment significantly influence the cooling energy demand of residential neighborhoods. In particular, courtyard with East-West orientation is a compact urban form with high building density, allowing a good shading on the internal facades of the courtyard and low cooling demand; in fact, it is a typical urban form of the historical districts in Turin.
Further developments of the GIS-based model are needed: (i) a sensibility analysis will be performed to evaluate the weight of the heat fluxes (*H/W* has a too high weight on solar gains); (ii) the thermodynamic system of glazing could be removed as it has a minimal impact on the energy demand of buildings; (iii) a more accurate description of the shaded environment exploiting the Solar Energy on Building Envelopes (SEBE) GIS-plugin.
Finally, the effect of the urban form to optimize the energy productivity of buildings will be investigated in order to improve self-sufficiency and self-consumption in densely built-up contexts. This GIS-based model could support policy makers by identifying energy efficiency measures and low carbon strategies that best suit each urban context, considering local constraints, and building codes: both in the design phase of new neighborhoods, and in the retrofit of existing buildings.

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