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Numerical assessment of heating energy demand for office buildings in Italy

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Abstract

Buildings energy consumption depends on several parameters, such as climate, envelope typologies, occupant behavior, intended use, etc.; assessment of the energy performance of a building requires substantial input data describing constructions, environmental contexts, thermo-physical properties, geometry, control strategies and several other parameters influencing the thermal balance. In the last years, several numerical approaches dedicated to building simulation have been tested developing specialized software. On the other hand, simplified building models permit the evaluation of indoor conditions and heating/cooling loads with a good level of accuracy and without excessive computational costs or user expertize. The authors tried to establish a set of simple correlations to permit a fast preliminary assessment of heating energy demand for office buildings. Data employed to build the correlations come from detailed dynamic simulations performed in TRNSYS 17 environment; these models were build according to the legal limits of Italian standards and laws concerning low energy requirements. The authors identified specific locations for different Italian climatic zones and simulated three models with different shape factors (S/V = 0.24, 0.5 and 0.9). The obtained results allowed to determine simple and direct correlations among heating energy demand, Heating Degree Days and S/V values.

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Keywords: heating energy demand; HDD; shape factor; dymanic simulation.

1. Introduction

In the European Union (EU), buildings account for about the 40% of the total energy consumption and they represent the largest sector in energy end-user area, followed by transport with the 33% [1]; whereas in terms of CO_2

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emission, buildings are responsible for about 36% of it. Energy is employed for different purposes, but the dominant energy end-use is space heating [1,2]. In order to achieve relevant saving of primary energy, several potential mitigation measures can be implemented involving the building envelope, indoor condition, heating/cooling systems, etc. [3]. In this context, the 91/2002 ‘‘Energy Performance of Buildings Directive’’ (EPBD) [4] has been enacted to introduce several requirements for new and existent buildings within EU; in Italy this Directive was transposed into the 192/2005 Decree [5]. The energy consumption of a building can be influenced by several parameters, such as climate, envelope typologies, age of construction, occupant behavior, intended use, etc.; a detailed evaluation of the energy performance requires several input data to solve the energy balance. In this context, many simulation tools have been developed to evaluate building performances [6], based on different approaches and with a lack of common language [7]: numerical approaches have been developed and tested [8-11], and most of them have been implemented in software dedicated to building simulation such as DOE-2, BLAST, Energy-Plus, TRNSYS, ESP-r, and SPARK [12]. On the other hand, simplified buildings models permit the evaluation of energy requirements and indoor conditions with an acceptable level of accuracy without excessive computational costs [13]. Indeed, in the common standards, steady state models are used to determine the energy performance of a building [14,15]. Thanks to their fast calculations, this approach assesses the energy performance in a simple way and conducts long term analyses on different scenarios involving several energy efficiency measures [16,17]. These kind of models are commonly used for preliminary building design and for scenario analyses; in particular, among the climatic parameters, the Degree Days (DD) indicator can be used to quantify the heating and cooling energy demands permitting, in a simple way, to obtain a first assessment of buildings consumption [18,19]. Many studies used DD for analyzing regional climate characteristics and to predict energy demand [20-22]. The determination of the energy performance of a building taking into account only on climatic context, may lead to an imprecise evaluation because it is totally unlinked to the thermophysical characteristics of the envelope and to the shape factor of the building. The following work rises in order to help the designer for a preliminary assessment of the energy performance of a non-residential building, designed as dictated by national law. The use of a simple and reliable correlation can provide the thermal energy requirements, allowing the designer to not use any simulation software, and then to accelerate the entire evaluation process. The presented study is based upon the development of a set of dynamic models of “ideal non-residential buildings” in TRNSYS software environment [23] built according to the energy legal limits of different climatic zones of Italian peninsula [24]. For a more general approach, authors have chosen three cities that represent the maximum, minimum and average Heating Degree Days (HDD) value for each climatic zone; furthermore, for each city, three models with different shape factors (S/V = 0.24, 0.5 and 0.9) have been simulated. The results obtained from the detailed simulations in TRNSYS have been employed to build strong correlations among heating energy demand, HDD and S/V values. In detail, applying the least squared method it was possible to identify simple correlations, valid for each climatic zone and for the Italian territory, obtaining high correlation coefficients R^2

Nomenclature

DD	Degree Days [°C ·day]
H_d	heating energy demand [kWh/m^2 year]
HDD	Heating Degree Days [°C·day]
R^2	correlation coefficient
S	surface area with thermal losses [m^2]
S/V	shape factor or losses surface to volume ratio or compactness [m^{-1}]
T_i	average daily temperature [°C]
T_r	indoor thermal comfort temperature [°C]
T_s	reference temperature [°C]
U_{floor}	floor thermal transmittance [W/m^{2}K]
U_{roof}	roof thermal transmittance [W/m^{2}K]
U_{wall}	wall thermal transmittance [W/m^{2}K]
U_{window}	window thermal transmittance [W/m^{2}K]
V	heated volume [m^3]
θ_1	correction coefficient [kWh/m^{2}year]

θ_2	HDD correction coefficient [kWh/K m^2 year]
θ_3	S/V correction coefficient [kWh/m year]

2. Simplified thermal balance of a building

Generally, heating energy requirements of a building are influenced by the transmission losses through the envelope, the energy gains due to solar radiation and the presence of people and strongly correlated to the climate context and the thermo-physical parameters. This last term is a practical index of the mean quality of the building envelope, not considering the geometry or the geographical positions of the building. A simplified approach generally does not evaluate the loss surfaces respect of the heated volume or the building shape factor. On the contrary, the surface area to volume ratio (S/V) is an important factor influencing heat losses and gains. The greater the surface area the higher the heat gain/ loss through it; small S/V ratio implies minimum heat gain and minimum heat loss. Obviously, use of compactness allows a more accurate assessment of the heating energy demand (H_d). Following this approach, the heating requirement is function of climate and shape factor:

$$H_d = f\left(HDD, \frac{S}{V} \right) \tag{1}$$

The authors have investigated the energy performance of three office buildings in different climate context and with different shape factor taking into account the hypothesis expressed in Equation (1), to identify a generic correlation that determines the heating energy demand of a non-residential building.

3. The Heating Degree Days

Degree Days for a location is defined as the sum, extended to all days of a conventional twelve-month period, of only the positive differences between the base indoor temperature and the daily average outdoor temperature. In the case of HDD the differences between outside and base temperature are computed only when the outside temperature falls below the base temperature, during the heating period. There are several ways to determine DD,: mean degree-hours as the Italian calculation method; the daily maximum and minimum temperatures; the mean daily temperature DD [25-28] or the direct calculation of monthly DD from mean monthly temperature and the monthly standard deviation [29]. However, it should be noted that the following Equation (2):

$$H_d = \sum (T_r - T_i)_+ \times 1 day \ \left[°C \cdot day \right] \tag{2}$$

where the subscript + denotes that only the positive values are summed, should always be the preferred option if suitable hourly data and adequate data processing tools are available. According to the definition of DD, for a given location, fixed a reference indoor base temperature T_r (20°C); DD are calculated according to the Equation (2), where the sum is extended to all days of the year, in which the difference between T_r and the average daily temperature T_i is lower than a second reference temperature T_s (12°C) conventionally fixed. The determination of the DD is fundamental in a correct evaluation of the energy needs of a building-system in relation with climate conditions. The attention to energy saving and the subsequent release of the first relevant standards was born in 1974 after the first world energy crisis; nowadays, the Italian law is based on the climatic zone indicated in [30].

3.1. The Italian climate context ant its national legislation

Italy is a peninsula located almost in the center of the temperate zone of the northern hemisphere that also includes two large islands: Sicily and Sardinia. Generally, it is possible to identify three big climate areas: in the north of the country, the climate is harsh, with very cold winters and very hot and particularly humid summers, due to the presence of Alps and Apennines. In central Italy, the climate is milder, with a smaller difference in temperature between summer and winter and a shorter and less intense cold season respect in the north; summers are longer, but the sultriness of the northern cities is mitigated by the sea. In southern Italy and the islands, winters are never particularly harsh, and spring and autumn temperatures are similar to those reached in the summer in other areas of Italy. According to the Italian national guidelines for buildings energy certification, it was possible to identify different climatic zones that (theoretically) have the same climate [31]. Employing the HDD, it is possible to identify six different climatic zones: zone A represents the hottest one and zone F represents the coolest. In the following table for each zone it is issued the daily hours of the heating system activity and the consequent yearly period.

Table 1. Italian Climatic Zones and characteristic.

Climatic Zone	From HDD	To HDD	During of heating season		Daily hours
			from	to	
A	0	600	1st December	15th March	6
B	601	900	1st December	31st March	8
C	901	1400	15th November	31st March	10
D	1401	2100	1st November	15th April	12
E	2101	3000	15th October	15th April	14
F	3001	∞	No limit		

The “National guidelines for energy certification of buildings” [24] requires that the evaluation of the Italian buildings performance is based on the comparison with a “reference building”. A “reference building” is a building identical from the point of view of geometry, orientation, geographical location, intended use and environmental context, having predetermined thermal and energy parameters in accordance with the legal limits [24]. In Table 3, in the “*limit”* columns, for each climatic zone are indicated the thermal transmittance values of external wall (U_{wall}), roof (U_{roof}), floor (U_{floor}) and of window (U_{window}).

4. The case study

To obtain reliable and useful mathematical correlations, authors deployed several detailed dynamic models of an “ideal office Building”. The model, designed in accordance to technical standard with high-energy performance, was implemented in TRNSYS 17 software. The following Fig.1 shows the TRNSYS model where the icon “building” is the “Type 56” that allows the detailed construction of the building model. The buildings models are characterized by an envelope with low thermal transmittance values, as depicted in the “model” columns of Table 4.

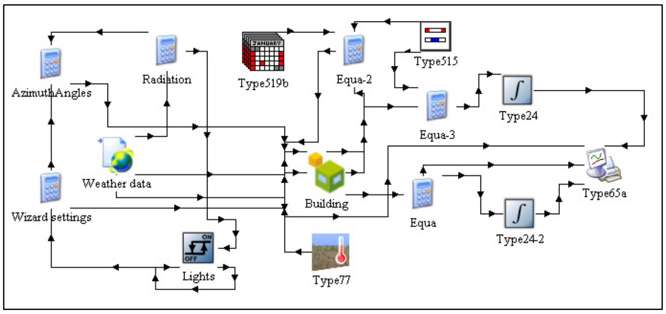


Fig. 1. TRNSYS model of the “ideal office building”.

To generalize the results, the "ideal office building" was created with three different shape factors (S/V=0.24, 0.5 and 0.9); each model has been simulated in five climatic zones from B to F of the Italian peninsula. Furthermore, three cities for each climatic zone have been chosen, identifying 3 different HDDs representing the maximum, minimum and average values. The climatic zone A was not simulated because in Italy there are only two cities belonging to this zone with similar HDD values (Lampedusa has HDD=568 and Porto Empedocle has HDD=579). In Table 2 are collected the Italian cities chosen for this work:

Table 2. Italian cities and HDD values.

Italian Climatic Zones									
B		C		D		E		F	
City	HDD	City	HDD	City	HDD	City	HDD	City	HDD
Messina	707	Cagliari	990	Genova	1435	Trieste	2102	Cuneo	3012
Palermo	751	Bari	1185	Firenze	1821	Torino	2617	Cortina	4433
Crotone	899	Termoli	1350	Forlì	2087	Bolzano	2791	Setriere	5165

The construction of each model has required the determination of:

- geometric characteristics of the building: width, depth, height, heated volume and losses surfaces;
- thermal-physical characteristics of building envelope: opaque and glazed surfaces (Table 3, "model" columns);
- the ratio between the opaque surface and glass surface (about 0.61);
- boundary conditions;
- internal and solar gains, air infiltration, switch on/off schedule of heating system, definition of the heating period. climatic context.

Table 3. Limit and model thermal transmittance values used in TRNSYS models.

Climatic Zone	A-B		C		D		E		F	
U value	limit	model	limit	model	Limit	model	limit	model	limit	model
	[W/m^{2}K]									
U_{wall}	0.45	0.444	0.38	0.379	0.34	0.336	0.30	0.297	0.28	0.276
U_{roof}	0.38	0.377	0.36	0.353	0.30	0.303	0.25	0.249	0.23	0.234
U_{floor}	0.46	0.445	0.40	0.385	0.32	0.307	0.30	0.287	0.28	0.268
U_{window}	3.2	2.76	2.40	2.26	2.00	1.76	1.80	1.76	1.50	1.40

Concerning climate, each model was simulated employing Meteonorm weather data [31]. Authors used the "Typical Meteorological Year 2 -TMY2" on an hourly time-step, of the last twenty years for the 15 Italian cities. For each simulated model, the heating system is turn on for 8 hours a day, from Monday to Friday, from 06.00 to 12.00 and from 15.00 to 17.00, not considering weekends and holidays. Solar gains, referring to the amount of energy released by solar incoming radiation through the glazed surface of the building envelope, were valuated directly by the dynamic simulation as a function of weather data, geometrical features of the building and surfaces orientation. Internal gains contributions were evaluated creating specific schedules for employment rate, electrical equipment and lighting system. In detail, the employment rate was estimated from 07:00 to 17:00, considering the reference values reported in Annex G of specific technical standards [14]; internal gains due to electrical equipment and lighting system, were implemented taking into account the utilization rate. The lighting system was modeled considering fluorescent lamps with a specific thermal heat flow of 5 W/m^2 ; electrical equipment contribution was implemented with partial or total use according to working hours, even assessing the radiative and convective contributions. Furthermore, even the infiltration losses were determined following Annex C of the standard [14]. Moreover, to evaluate the average energy performance of a building taking into account incident solar radiation, each model was simulated 8 times, varying the orientation of the building by 45° and averaging of the obtained results. Finally, integrating and averaging the simulation results, the annual heating energy demand has been calculated; Table 4 collects the results obtained from the dynamics simulations, for each city and each S/V.

Table 4. Thermal heating energy demand in each location and for different S/V [kWh/m^{2}year].

Heating energy demand											
Climatic Zone	City	HDD	S/V			Climatic Zone	City	HDD	S/V		
			0.24	0.5	0.9				0.24	0.5	0.9
B	Messina	707	0.2374	4.8761	5.9838	E	Trieste	2102	1.8282	7.0687	9.3932
	Palermo	751	0.2241	4.4872	5.2404		Torino	2617	5.1640	9.0622	16.0303
	Crotone	899	1.3873	6.6259	10.3095		Bolzano	2791	5.1647	8.6190	15.2653
C	Cagliari	990	0.0607	4.6004	3.2785	F	Cuneo	3012	1.2772	7.8831	6.7036
	Bari	1185	0.3884	6.4473	5.9554		Cortina	4433	9.6087	12.7309	24.5134
	Termoli	1350	1.6768	7.3603	10.4751		Sestriere	5165	10.6578	15.71.60	21.8505
D	Genova	1435	0.6317	6.1345	6.7350						
	Firenze	1821	0.8277	6.8839	7.5827						
	Forlì	2087	4.1129	8.7178	16.1796						

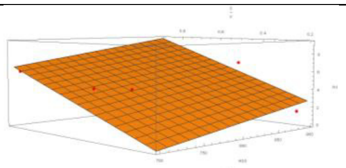
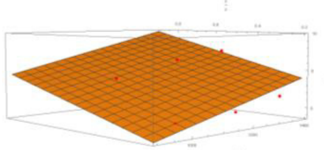
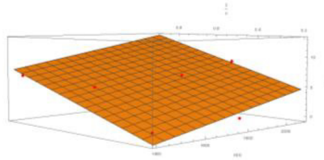
5. Results

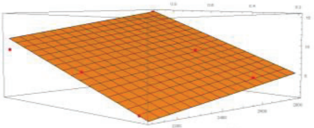
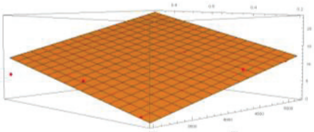
The previous results have been condensed in simple correlations useful to evaluate the thermal energy performance of an office building in a specific climatic zone and for the entire Italian Peninsula. In the first analysis, the data concerning each zone have been fitted with the following explicit function of HDD and S/V (a plane in three dimensions space):

$$H_d = \theta_1 + \theta_2 \cdot HDD + \theta_3 \cdot \frac{S}{V} \tag{3}$$

Least squared method has been applied to data obtained from TRNSYS simulations to determine the values of θ_1, θ_2 and θ_3. In the following Table 5 are collected the θ value for each equation pertaining each climatic zone; furthermore fitted plans and points, and correlation coefficient are drawn. In all cases, R^2 values vary from 0.895 to 0.987.

Table 551. Results of H_d Equation for each climatic zone.

Climatic zones	H_d equation	Plan	R^2
B	$H_d = 0.014 \cdot HDD + 9.493 \cdot \frac{S}{V} - 11.927$		0.941
C	$H_d = 0.011 \cdot HDD + 8.222 \cdot \frac{S}{V} - 12.529$		0.895
D	$H_d = 0.007 \cdot HDD + 12.142 \cdot \frac{S}{V} - 13.520$		0.929

E	$H_d = 0.006 \cdot HDD + 14.315 \cdot \frac{S}{V} - 13.684$		0.987
F	$H_d = 0.005 \cdot HDD + 15.755 \cdot \frac{S}{V} - 18.638$		0.963

To generalize the results and to deploy a single correlation, valid for the entire Italian peninsula, all data were collected in a matrix with 45 rows and 3 columns, where: in the first column are collected the HDD values, in the second column are collected the S/V values, in the third column are collected the simulated H_d values and in the rows there are the cities (15 cities for each S/V value). By this way, applying the same equation form identified in Equation (3), it was possible to determine the following correlation:

$$H_d^* = -4.619 + 0.024 \cdot HDD + 12.148 \cdot \frac{S}{V} \tag{4}$$

Fig.2 (a) plots the plan of the Equation (4) and the reliability of the correlation is guaranteed by the high value of R2=0.898. Fig. 2 (b) shows a good accordance between simulated and calculated data. Even the distribution of the fit residuals at different data points presents a limited variability in Fig. 2 (c).

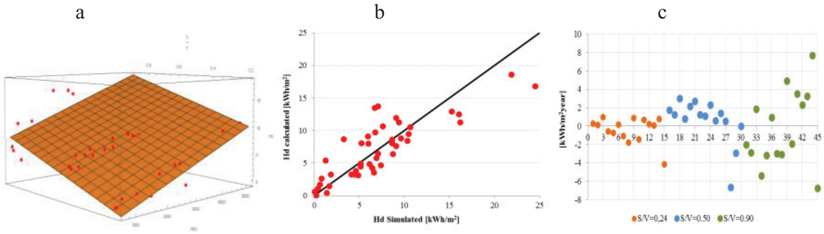


Fig. 2. Plans (a), correlation degree (b) and the fit residual between simulated and calculated data (c)

6. Results

The aim of this study was to determine simple and reliable mathematical correlations that allow a generally assessment of the thermal energy performance for an office building designed according to the high-energy performance of the Italian standards. The solution of the energy balance of a building-plant system is a complex procedure; it is necessary an accurate knowledge of the physical phenomena, the implementation of this in specific tools; furthermore, dynamic simulations require expert users. The following work rises in order to help the designer for a correct and fast preliminary assessment of the energy performance of a non-residential building located in the Italian peninsula, following the limits dictated by the law. The use of a single equation, with a good correlation coefficient, provides the thermal energy requirements, allowing the designer to not use any simulation software, and then to accelerate the entire diagnosis or assessment process. Authors built several dynamic models of an "ideal non-residential building" in TRNSYS, according to the energy requirements of the Italian legal limits of energy efficiency in buildings. For each Italian climatic zone, from B to F, the authors have chosen three cities that represent the maximum, average and minimum value of HDD range, each model with different shape factors (S/V = 0.24, 0.5 and 0.9). The generalization of the simulation results permits to define five correlations, one for each climatic zone, that allow an immediate assessment of the heating energy demand. Finally, all data have been used to extrapolate a relationship valid for the entire Italian peninsula. The feasibility of these correlations are guaranteed by very high values of R^2 coefficients.

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