Influence of the boundary conditions on the definition of a reference residential building for the Italian context

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Abstract

Numerical simulation is nowadays a fast and well suited practice, useful to design buildings and thermal energy systems, being also recognized in international standards (e.g. UNI EN ISO 13790). However, monitoring data often show large divergences with respect to simulated data; this is especially true when highly efficient systems are considered. Moreover, when the effectiveness of a particular technical solution (e.g. thermal plant, insulation approach, etc.) has to be verified, an accurate prediction of the loads has to be computed. In this sense, the definition of a reference building is fundamental, as much as a correct assessment of constructive, climatic and inhabitants' behavioural parameters that mostly affect system's operation. This modelling phase represents, on the one hand, the main part of the simulation work, on the other, the way to adopt solutions that assure the lowest Primary Energy consumption. In this paper, a sensitivity analysis is presented with respect to the energy performance of a two-storey single family house; seasonal and yearly operations are reported, in terms of the final energy consumption. Two buildings placed in Bolzano and Rome, with the same size and construction characteristics according to the Italian standard (DM 26/01/2010), have been taken as reference points. Starting from these reference buildings, a number of parameters have been varied: the constructive characteristics (insulation properties and thickness, glazed area and infiltration), the management characteristics (natural free ventilation) and finally the climatic data used. The sensitivity analysis has been carried out with the Morris Method, by comparing average and standard deviation of the variation of the final energy with the aim to derive qualitative information on the effect of the single parameter on the model's outputs. This process is fundamental for increasing the sensibility on the relevance of assumed boundary conditions and moreover, helpful for the designer's knowledge of what the parameters are to be tuned first in order to reach a given energy performance.

1. Introduction

The building sector is responsible for 40% of the total energy consumption at the European level (2020-20-30-2050). To reduce the building's energy need and plan an efficient integrated system, knowledge of the behaviour of the building is essential.

The numerical simulation models of buildings are well suited for understanding the energy consumption and predicting the time-varying loads for heating, cooling and lighting. In this context, the predicted energy needs are one of the key issues for the performance evaluation of different technical integrated solutions through dynamic simulations.

Results given by these models are strictly connected to the assumption made during the design phase. Furthermore, the boundary conditions imposed strongly affect the behaviour of the numerical model.

In order to understand the influence of a certain parameter on simulation outputs, a sensitivity analysis has been conducted by using the results of a residential building modelled in Trnsys for two different Italian climates.

Three main aspects have been investigated: (1) building inhabitant behaviour, (2) envelope construction and (3) climatic data. The first issue can affect the model results since, during the design phase, a typical profile of building usage has to be selected, for example the infiltration rate, the schedule of internal gains (occupants or electrical appliances) and the adoption of the night ventilation strategy. The second aspect is related to the comparison between the building's numerical model and the constructed one. For this aspect, the focus is given to shading devices, internal walls and the real transmittance of opaque walls. Envelope could create a large difference not only in terms of energy demand between model results and real behaviour; this is even more visible when the performances of an integrated system have to be studied. Thirdly, huge difference could be found on simulation outputs using climatic data generated from different stochastic algorithms. In general, during design phases of a numerical model, inaccurate analysis are performed on the climatic data selected to use. Referring to a specific installation, the climatic profile data can affect the loads profile of the system.

The sensitivity analysis presented in this paper has been based on the Morris Method. This methodology can increase the awareness about the effect of the single parameter simulation results. It is used to prioritize the parameters, giving information related on their effects on the outputs (Morris, 1991). In the case studied here, the list of investigated parameters is described in detail in the next sections, with a specific focus on the heating and the cooling final energy.

2. Methodology

2.1 Sensitivity analysis with the Morris Method

The Morris Method (MM) belongs to the screening methods (Saltelli, 2005) where all parameters are varied "one at time" (OAT). The main objective is to isolate those inputs that can affect the response of the model by classifying their influence as (1) negligible, (2) linear or additive and finally (3) nonlinear or involved with some other factors.

The elementary effect of the MM is defined for the i parameters, on the k input analysed:

$$EE_i = \frac{\left[y\left(x_1, \ldots, x_{i-1}, x_i + \Delta, x_{i+1}, \ldots, x_k\right) - y(\overline{x})\right]}{\Delta} \quad (1)$$

Varying the x_i within a realistic range Δ, using r_i different number of steps for each i parameter, the Elementary Effects EE_i are evaluated. With the Elementary Effects of each input, the average μ_i and the standard deviation σ_i of the single elementary effect EE_i are then computed.

$$\mu_i = \frac{1}{r_i} \sum_{t=1}^{r_i} EE_{i,t} \quad (2)$$

$$\sigma_i = \sqrt{\frac{1}{r_i - 1} \sum_{t=1}^{r_i} \left(EE_{i,t} - \mu_i\right)^2} \quad (3)$$

The μ_i (eq. 2) is the mean parameter influence on the output, while the standard deviation σ_i (eq. 3) gives an idea on the nonlinear behaviour or interaction with other factors of the input.

The use of the average of the absolute elementary effect μ^*_i (eq. 4) is suggested (Campologo, 2007), rather than μ_i, to prevent the possible error during the sum of the EE_i with a negative sign, which presents a decreasing effect. Plotting the value of σ_i related to the absolute value of the mean μ^*_i, the inputs closest to the origin indicate less influence on the output.

$$\mu^*_i = \frac{1}{r_i} \sum_{t=1}^{r_i} \left|EE_{i,t}\right| \quad (4)$$

2.2 Case study

The sensitivity analysis has been performed on the Trnsys numerical model of a residential building about 180 m^2 divided over two storeys. The net volume of the building is around 600 m^3 and the ratio between external surface and gross volume (S/V) is around 0.7. The percentage of transparent surfaces on the different orientations is around 6% on the north, 10% on the east and west and 20% on the south. Heating and cooling are delivered to the internal zone through a radiative low temperature floor.

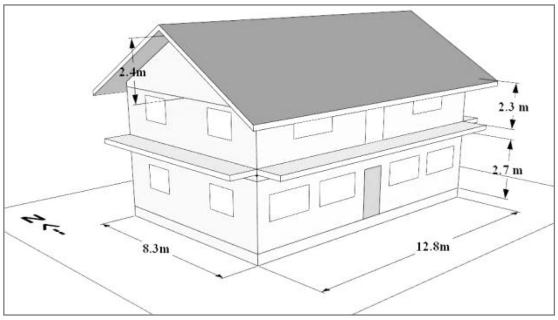

Fig. 1 – Residential building analysed.

The envelope characteristics considered are usual established massive wall stratigraphy, with an insulation thickness that allows to reach the limits imposed by the norm (DM 26/01/2010). The characteristics of the exterior walls, roof and floors are reported in the following table for the two Italian climatic zones analyzed (Rome and Bolzano).

Elements	Characteristics	Bolzano	Rome
External Walls	U [W/(m²K)]	0.27	0.29
Roof	U [W/(m²K)]	0.24	0.26
Ground Floor	U [W/(m²K)]	0.30	0.34
Windows	U [W/(m²K)]	1.80	2.00
	g [-]-	0.597	0.613

Table 1 – Envelope characteristics for the two climatic zone (DM 26/01/2010).

In order to simulate balconies and roof overhang, on the south, west and east orientations a fixed shading is considered. Internal gains and the schedule of presence considered are in accordance with the UNI/TS 11300-1. These values are typical for residential buildings, assuming that 60% of the building area consists of bedrooms while the remaining 40% is for living space. This leads to a mean daily value for the internal gains of 5.2W/m². In both climates, an infiltration rate equal to 0.45 ACH is considered. During the night in summer, a free natural ventilation has been additionally considered. This night ventilation air change rate has been computed using a free driven tilted ventilation approach (Weber, 1997). The free night ventilation is activated if the following conditions are met:

- Night time: between 21.00 and 08.00;
- Average of external temperature over 24 hours is greater than 12°C;
- Room temperature is above 23°C;
- Temperature difference between internal and external is above 2°C.

When this happens, an air exchange rate through the windows is calculated as a function of the internal-external temperature difference, the window shape and the opening tilt angle.

2.3 Weather data description

In building simulations, the weather data used for reproducing the climatic conditions affect the behaviour of the numerical model computed. In order to better understand the level of this influence, two "typical year" profiles have been considered. This climatic data, generated using the Meteonorm software (Meteonorm, 2012) are based on a stochastic analysis of 10 years of data for temperatures (from 2000 to 2009) and on 20 years of data for radiations (from 1986 to 2005). The two profiles considered are:

"Standard" weather data (STD), which is an hourly profile created using the models of (Remund, 2008) (Perez, 1991) for calculating solar radiation, while ambient air temperature is derived from the mean of extreme values over 10 years.

"Extreme" weather data (EXTR), which is an hourly profile generated by hourly extreme solar radiation and ambient air temperature, which correspond to extreme (minimum ambient temperature and radiation during wintertime and vice versa for summertime) values of the 10 years. With this approach, the year does not aim to represent a typical year, but to be a "worst" case scenario.

In the following graphs the frequency of the dry bulb temperature (DBT) and global horizontal radiation (GHR) are reported for the two locations analysed. The following graphs show columns related to frequency and curves that represents the cumulative frequency of the single series of data considered.

Analysing the distribution of DBT of Bolzano (Fig. 2) the EXTR data is clearly distributed in the low temperatures (extreme winter conditions) and in the high temperatures (extreme summer conditions). In winter, the number of hours where the temperature is below 0°C moves from 18% (790 h) to 32% (1300 h). During summer, analysing the temperature above 24°C, the hours move from 17% (770 h) to 35% (1600 h). The cumulative curve reflects this behaviour (higher at low temperature and lower at high temperature).

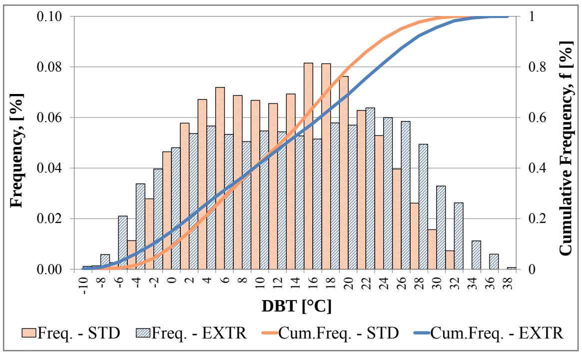

Fig. 2 – External Dry Bulb Temperature – Bolzano.

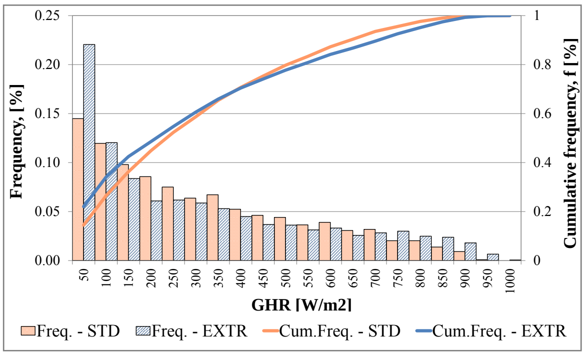

Fig. 3 – Global Horizontal Radiation – Bolzano.

Also the GHR for the EXTR data displays the percentage of radiation bigger for a higher level of GHR. It is interesting to note these differences also in Table 2, where the difference of the two climatic data is shown in terms of max. and min. temperatures, HDD and GHR computed for the whole year.

For Rome the differences between the two profiles are not so significant. Here, the two climatic data have almost the same distribution, with a small difference in the highest DBT and GHR. During the summer periods the extreme profile counts, for temperature above 28°C, 450 h, corresponding to 7% of the summer, while in the standard profile the hours are 312 equal to 5%. The HDD analysis shows a small difference between STD profile and EXTR data analysis.

Bolzano		STD	EXTR
T_{min}	[°C]	-8.75	-11.13
T_{max}	[°C]	31.75	36.34
$I_{g,hor}$	[kWh/m²yr]	1251	1331
HDD $_{12/20}$		2711	2870

Table 2 – Temperature, total energy on the horizontal surface and HDD – Bolzano.

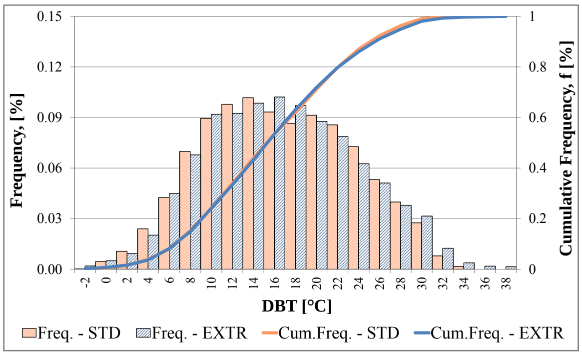

Fig. 4 – External Dry Bulb Temperature – Rome.

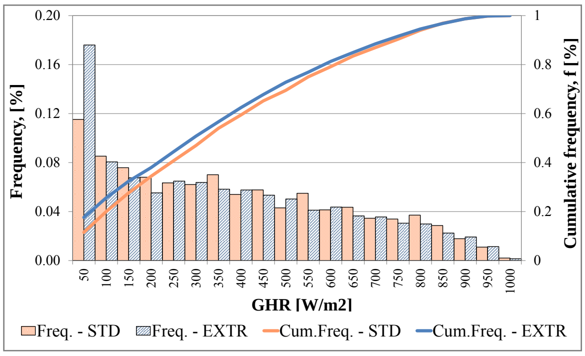

Fig. 5 – Global Horizontal Radiation – Rome.

Rome		STD	EXTR
T_{min}	[°C]	-2.3	-3.9
T_{max}	[°C]	33.1	37.4
$I_{g,hor}$	[kWh/m²yr]	1561	1562
HDD $_{12/20}$		1371	1299

Table 3 – Temperature, total energy on the horizontal surface and HDD – Rome.

2.4 Sensitivity analysis sets

The sensitivity analysis has been conducted through a campaign of simulations in Trnsys. The inputs of the model analyzed, the range and step considered are summarized in *Table 4*. The transmittance of opaque surfaces are the average of external walls, roof and floor weighted with the correspondent area of exchange for the two climatic zones studied. The overhang length is 1m, chosen for the simulation of the effect of balconies and roof overhangs. The internal gains are the average on the single day for a detailed approach (UNI EN ISO 13790). The night ventilation input is related to the operable window area ranging from 0 to 4 m². The orientation input is considered using the angle between the south orientation and the south façade of the reference. The fenestration ratio is the sum of all the windows on the different orientation.

n	Parameters	Ref.	Min	Max	Step
1	Overhang [m]	1	0.6	1.4	0.2
2	Internal Gains [W/m²]	5.2	2.6	7.8	1.3
3	Infiltration rate [ACH]	0.45	0.25	0.65	0.1
4	Night ventilation [m²]	4	0	4	1
5	Orientation [°]	0	0	360	45
6	Transmittance (Bolzano) [W/m²K]	0.269	0.161	0.377	0.054
	Transmittance (Rome) [W/m²K]	0.284	0.170	0.398	0.057
7	Fenestration ratio [m²]	27	21.6	32.4	2.7
8	Thermal inertia [kJ/K]	$2.2 \cdot 10^5$	$2 \cdot 10^5$	$2.5 \cdot 10^5$	$1 \cdot 10^4$

Table 4 – Parameters investigated and range of variation for Bolzano and Rome.

The output used for sensitivity analysis of the system analyzed is the end energy demand for heating and cooling of the building with the set point of internal temperature of 20°C for winter and 24.5°C for summer. The distribution system considered is a radiative low temperature floor with the inlet temperature imposed using a climatic curve function of the external temperature.

3. Results and discussion

3.1 Analysis on weather data

A first analysis on the effect of the climatic data on the energy demand has been conducted and the comparison is reported in *Table 5*. Here, for Bolzano, the effects shown in the weather data description (higher frequency for low and high temperatures) are reflected in a twice cooling energy demand while the heating demand increased by about 20%.

Also for Rome, the effect of the analysis made on the weather data is visible on the heating and cooling demand. In this case, however, for the two climatic profile used, the heating and cooling energy needs are similar. A small difference between heating energy loads reflects the HDD analysis reported in Table 3.

	Weather	Unit	Bolzano	Rome
q_{heat}	STD	[kWh/(m²yr)]	54	26
q_{heat}	EXTR	[kWh/(m²yr)]	63	24
q_{cool}	STD	[kWh/(m²yr)]	12	18
q_{cool}	EXTR	[kWh/(m²yr)]	23	18

Table 5 – Final Energy for heating and cooling with different weather data.

3.2 Sensitivity analysis

Using as a reference the building with standard weather data, the results of the sensitivity analysis are presented here. The graphical representation of the MM is a scatter graph, where each point plotted is related to the elaboration on elementary effects of each parameter analyzed. The graph shows the absolute mean on the x-axis and the standard deviation on the y-axis. Values closer to the origin represent parameters with less influence and linear effect on the output. A dotted line is also reported, representing the threshold between linear or non-linear influence on the output.

Two different outputs are evaluated in order to understand the effect of the parameters: seasonal cumulated heating and cooling demands.

Recalling the definition given for the elementary effect EE for a certain parameter analyzed, this represents the output variation when the input moves from a minimum to a maximum value.

Starting from the analysis on the heating demand, for both climatic locations (*Fig.* 6 and *Fig.* 7), a linear effect with high mean value is visible in the graphs with regard to the envelope parameters (transmittance and infiltration) and inhabitants' behaviour (internal gains).

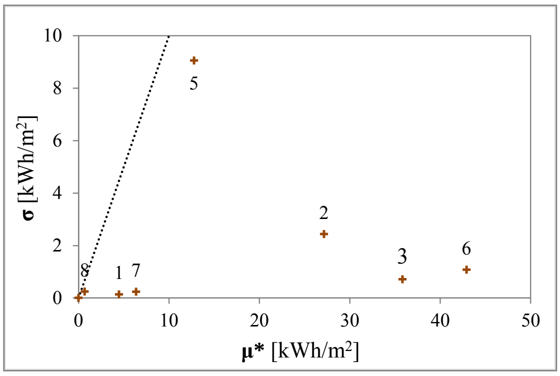

Fig. 6 – Estimated mean (μ*) and standard deviation (σ) for each input factor on heating energy demand – Bolzano.

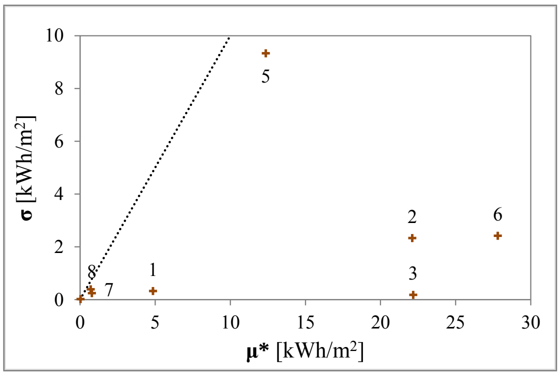

Fig. 7 – Estimated mean (μ*) and standard deviation (σ) for each input factor on heating energy demand – Rome.

Secondarily the orientation of the building has an effect close to nonlinear behaviour or correlated with other parameters. A small linear effect is noticeable with regard to the two envelope parameters (variation of shading device and fenestration ratio); the effect of night ventilation is null because the conditions for simulating this effect are not reached during winter, as reported in the case study description.

For the cooling analysis, the internal gains have the highest impact on the energy demand for both buildings located in Bolzano and in Rome (*Fig.* 8 and *Fig.* 9). The variation of the fenestration ratio, differently from what is shown in the heating analysis, has a strong linear influence on the cooling energy because this parameter is directly connected to the solar gains. The orientation has a significant linear influence. The parameters that show a minor influence, compared with the analysis on the heating demand are the transmittance and the infiltration. Their minor effect is mainly due to the lower difference between internal and external temperature in the summer. For the same reason, also the variation of the operable window area, simulating the night ventilation, has a small impact on the cooling demand.

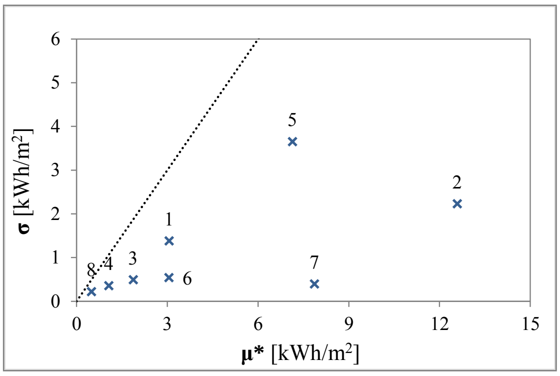

Fig. 8 - Estimated mean (μ*) and standard deviation (σ) for each input factor on cooling energy demand– Bolzano.

A ranking of the design parameters influencing the sensitivity of the energy used for heating and cooling is reported in Table 6. Here, the predominant parameters are clearly reported for both output and climatic location considered. As mentioned before, the envelope characteristics and behavioural aspects have a strong influence, on the one hand, on the heating loads with transmittance of opaque walls, infiltrations and internal gains. On the other, the cooling demand is mainly affected by internal gains and fenestration ratio. The orientation of the building is an important parameter for both analysis of the heating and cooling needs.

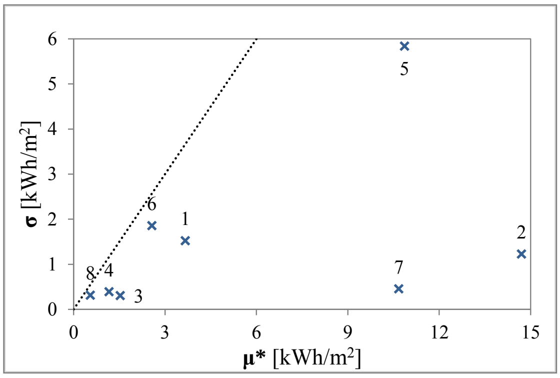

Fig. 9 – Estimated mean (μ*) and standard deviation (σ) for each input factor on cooling energy demand– Rome.

Parameters	**Rank Heating**		**Rank Cooling**	
	Bolzano	**Rome**	**Bolzano**	**Rome**
Overhang [m]	6	5	4	4
Internal Gains [W/m²]	3	3	1	1
Infiltration rate [ACH]	2	2	6	6
Night ventilation [m²]	8	8	7	7
Orientation [°]	4	4	3	2
Transmittance [W/m²K]	1	1	5	5
Fenestration ratio [m²]	5	6	2	3
Thermal inertia [kJ/K]	7	7	8	8

Table 6. – Ranking parameters

4. Conclusions

Numerical simulation models are nowadays well suited for predicting the energy consumption of buildings and evaluating the performances of different technical integrated solutions. The building performances simulated are strictly connected to the boundary conditions chosen during the model's definition phase.

A correct choice of these parameters affect the building loads and the performances especially when an integrated solution is studied. In the early stage, a deeply analysis of the boundary conditions, e.g. the weather data used in the simulation, is strongly recommended in order to understand in which conditions the performance of the building is evaluated. The climatic data considered strongly affect the heating and cooling demand of the building.

The effects of the parameter's variation on the model's output is fundamental in order to understand the significance of each studied parameter. The Morris Method shows a strong influence of the envelope and construction aspects (transmittances, infiltration, orientation, fenestration ratio and shading devices) and behavioural aspects (internal gains) on the heating and cooling demand.

In order to reach a certain energy performance target or to modify the building numerical simulations, this awareness allows for the prioritization of the studied parameters and the tuning of the models starting from the most important parameters. Furthermore, the knowledge of the real value of these parameters and the effects produced when they move in a certain range of variability allow, in particular during the early design phases, for the following of a more or less conservative design approach to the building or the integrated system.

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