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Building energy efficiency assessment by integrated strategies: dynamic simulation, sensitivity analysis and experimental activity.

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Abstract

Thermal and energy dynamic analysis of buildings is a well-established procedure to evaluate the effective building energy performance, considering real climate. The proposal of new technical solutions and innovative strategies to be applied for both summer and winter period has a fundamental role also considering the IPCC suggestions and the EPBD European Directive implementation.

In this paper a synthetic but also exhaustive method for thermal dynamic analysis of buildings is proposed. It is based on performance levels assignment, defined by proper non-dimensional indexes (TDI, Thermal Deviation Index) that allow to express the building behavior and the sensitivity analysis results, in relationship to the climatic context.

The proposed methodology is then applied to different case studies consisting of numerical prototypes of free-running residential buildings to evaluate first the architectural shape role and then the sensitivity of different envelope features, characterized also by experimental measurements conducted on real Italian residential buildings. The prototypes are designed to optimize respectively summer or winter energy performance or to represent the typical Italian house before and after energy efficiency regulation coming into force. To better define some important parameters necessary to calibrate the numerical models, experimental activities are carried out. In particular, thermal insulation level and roof reflectance, characterized by means of spectrophotometrical measurements, are measured both in the case of an old traditional Italian building and in the case of a new one.

The results of the dynamic analysis, concerning all the considered variables (mass and insulation, roof reflectance, Solar Heat Gain Coefficients of glasses, weather data, etc.) are defined by TDI values that make it possible to evaluate and to compare the role of each element for defining the building thermal performance, also related to the specific climatic context.

The results obtained using the proposed method are also compared with those obtained from existing procedures. In particular the TDI values are correlated to an adaptive comfort indicator, for verifying how much the TDI could be effective for evaluating free-running buildings thermal performance during both summer and winter period.

Keywords

Building energy performance, dynamic simulation, sensitivity analysis, envelope, cool roof.

1. Introduction

The International Energy question especially regarding the building sector has become a really important focus, both for designers and researchers, also considering the Fourth Report by

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Intergovernmental Panel on Climate Change (IPCC) [1]. It deals with the enormous potential of buildings in terms of Green House Gasses emissions reduction, achievable also applying a whole building energy design concept [2] different from a simple addition of disconnected parts.
All over the world the interest tries for acquire skills able to integrate and optimize all the possible interconnecting properties also during the earlier design phases [3]. By now it is clear that all the decisions taken in the early stages of the architectural process affect both indoor thermal comfort and building energy efficiency, that could not be independent also from the environmental stresses, typical of each macroclimate region [4] and also of every different outdoor microclimate [5]. Elements contributing to the creation of energy-efficient buildings are for example: architectural shape and "passive design" techniques, technical solutions both for the opaque and the transparent "intelligent façade", innovative materials, plants interaction strategies and multi-energy systems in buildings [6,7]. All these elements have also to be considered both in summer and in winter period, taking into account realistic and peculiar to the site climatic conditions [8].
The work idea begins from this research start point, considering the necessity to cut out the gap between building architecture, dynamic simulation procedures and energy systems design [9]. So this paper proposes a method to evaluate building thermal global performance after dynamic simulation, to be applied also for sensitivity analysis and optimization procedures. This method expresses the performance level using an objective function numerical value characterized by an immediate meaning. In this way the design process could be seen as an integrated procedure to optimize all the variables [10] defining a multivariable solution regarding materials, envelope, glazing and shading systems, energy plants, overall aimed to the optimum comfort level and the minimum energy consumption as well.
This system approach for the definition of a performance index, and so an objective function value, needs dynamic simulations results, like for example an indoor temperature trend, for every thermal zone. In this study the proposed methodology aims to define a valid criteria to compare simulation outputs with building qualitative objectives [11]. The index-objective function considers the operative temperature as the control parameter of indoor environment [12], because an efficient control on operative temperature allows to express a relationship between thermal performance, thermal comfort and indoor quality, discussed at the end of this work. The standard European reference for the assessments of the global indoor quality considered in this study is the EN 15251 [13]. It is founded on the adaptive comfort approach [14] to define the acceptable indoor temperature for free-running buildings, that could be representative of the residential buildings without mechanical heating-cooling systems evaluated in this paper [15]. This approach allows to consider the running mean outside temperature, that is fundamental for naturally ventilated case studies because this assessment is based on variables according to local climate [16], that is an important element of dynamic simulations.

2. Purpose of the work

The purpose of this study is to propose a simple but effective method to guide the evaluation of building thermal performance after dynamic simulations and to express the results using a concise non-dimentional objective function. The proposed index could be used to define the thermal global performance of both existing and new buildings, of the whole structure or different parts of it, or various optimization strategies.
In this paper the methodology is explained and applied to different case studies represented by free-running residential buildings in Italy, simulated by EnergyPlus [17] in three different climatic contexts: the city of Bolzano in the North of Italy, Perugia in the Center and Palermo in the South.

The software choice has been an important element of this analysis. EnergyPlus qualities [18,19] seem to correspond to this work needs to simulate energy flows through-out a building. This powerful tool is based on thermal zone heat balance model, considering a uniform temperature throughout each zone, a uniform surface temperature, a uniform long and short wave irradiation, diffuse radiating surfaces and one-dimensional heat conduction. Even if all the local phenomena are considered really important to define buildings energy efficiency, in this work, proposing a general assessment method, thermal bridges influence and CFD applications are neglected. However it is possible, and it could be interesting, to apply this method together with CFD simulation in a future development of this research, considering that ES-CFD coupling simulations provide complementary data for defining building thermal performance [20].

Dynamic simulation procedures by EnergyPlus are first applied to three different building shapes in three different climate contexts, to evaluate the architectural role by building simulation during the conceptual design stage [21]. Using the performance index values obtained from the simulations results, the best architectural layout could be chosen for each climate. Then the assessment method is applied to sensitivity analysis regarding the most performing shape. The proposed index was also useful to express the Output Parameter for defining the Influence Coefficient [4] and so the “sensitivity index” adopting an OAT-method (One parameter At a Time, [22]).

Applying GSA-approach (Global Sensitivity Analysis, [23]) to organize building simulations outputs, it was possible to assess every input influence, varying one input at a time in a specific range. This range is chosen considering the real variability of these properties on existing Italian residential buildings. The considered inputs in this study regard envelope properties, such as thermal capacity and insulation level, SHGC (Solar Heat Gain Coefficient) of windows glasses and shading system properties, that are well definable in EnergyPlus environment. Particular attention is paid to the roof solar reflectance [24,25,26].

The relation between optical properties and building thermal performance is by now explored [27] and cool roof coatings are considered effective, and maybe also cheap, ways to optimize energy consumption especially during summer. In this work reflectance property [29] was calculated about four different kinds of typical Italian traditional tiles, after spectrophotometrical in lab analysis [29,30,31,32].

Other experimental measurements are conducted regarding the opaque envelope transmittance measurements [33]. Two typical real houses are chosen to better define the range extremes [34]: a new one, built on 2009 according to the most recent Italian energy standards [35] and classified in the best efficiency quality category called “A” [36]. The second house was built on 1973 without any insulation panel, before every energy efficiency laws coming into force and it could represent the opposite transmittance range extreme.

All the parametric and sensitivity analysis results are defined by different values of the TDI (Thermal Deviation Index) proposed, representing the building performance considering the climatic context role.

To validate this method applicability and utility, the obtained assessments are then compared with another performance indicator commonly used in this field, degree hours criteria, typically used for thermal comfort long term assessments with adaptive approach [13].

3. Method description

The proposed methodology is based on the building dynamic analysis in real climatic conditions.

The procedure is composed of:

- preliminary study and adaptation of the method considering the specific aim to pursue;
- prototypes or real buildings simulation within a dynamic simulation environment;

- evaluation of possible optimization solutions design, starting from different tools evaluation, like thermal balances of the envelope elements, daily temperature trends varying the architectural shape, trying to receive and work out effective design optimizing strategies guidelines;
- building performance representation using the Thermal Deviation Index specific of each prototype ($TDI_{building}$) and of each different strategy simulated;
- evaluation of every strategy effect and sensitivity, studying building in an independent way respect to the climatic context, to verify the real building performance not influenced by particular environmental factors, useful especially during comparative analysis in different climatic contexts. Also in this case the performance is expressed by another Thermal Deviation Index specific of each prototype in relation to the site ($TDI_{building\text{-}site}$);
- final study of the results and classification of the properties. This step could actually lead to define the best solutions for performance improvement, suitable both to existing buildings and to guide the design process of new buildings at an early stage.

3.1 Building Thermal Deviation Index ($TDI_{building}$)

The fulcrum of the proposed procedure consists of the dynamic analysis both on seasonal and annual periods. The case studies results are then defined by different $TDI_{building}$ levels. This important indicator represents the distance from the thermal target condition of indoor environment, both in terms of frequency and intensity of the gap.
In this study the thermal target is expressed by Operative Indoor Temperature seasonal ranges, one is typical of winter condition and a different one for summer analysis, as explained in EN 15251 European Standard [13].
$TDI_{building}$ is expressed in this way:

$$TDI_{bui,\,seas} = \frac{\int_{P_{hot}-bui}\left[f\left(T_{O\text{-indoor}}\right)-T_{O,\,MAX\text{-seas}}\right]d\tau + \int_{P_{cold}-bui}\left[T_{O,\,MIN\text{-seas}}-f\left(T_{O\text{-indoor}}\right)\right]d\tau}{TDI_{BC,\,seas}} \cdot \frac{t_{seas}-t_{Target\text{-}bui,seas}}{t_{seas}} \quad [-] \qquad (1)$$

Where:
$T_{O\text{-indoor}}$ is the indoor operative temperature, calculated in the middle of each thermal zone. This parameter defines the indoor thermal environment in this study;
$T_{O,MAX\text{-seas}}$ and $T_{O,MIN\text{-seas}}$ are the highest and the lowest value of the indoor operative temperature target range. Maximum values considered are 299K and 298K and minimum values are 296K and 293K respectively for summer and winter conditions [13];
t_{seas} e t_{year} are the seasonal period and the annual periods of the analysis respectively;
$t_{Target\text{-}bui,seas}$ is the period during which the $T_{O\text{-indoor}}$ is included in the thermal seasonal target.
The summer thermal seasonal target is 296-299K and the winter one is 293-298K [13].
$P_{hot\text{-}bui}$ and $P_{cold\text{-}bui}$ are the integration domains in (1). In these periods the $T_{O\text{-indoor}}$ is out of the seasonal thermal target. They are defined in (2) and (3):

$$P_{hot-bui} = \left\{\tau \in \left[0, t_{seas}\right]: f\left(T_{O-indoor}\right) \geq T_{O,MAX-seas}\right\} \quad [h] \qquad (2)$$

$$P_{cold-bui} = \left\{\tau \in \left[0, t_{seas}\right]: f\left(T_{O-indoor}\right) \leq T_{O,MIN-stag}\right\} \quad [h] \qquad (3)$$

So the Thermal Deviation Index (1) is a non-dimensional index representing the product of two terms. The first one is the ratio between the sum of the areas in which the $T_{O\text{-indoor}}$ is out of the thermal target, and a base case index $TDI_{BC,seas}$. This index value could be calculated both for seasonal and annual analysis in this way (4):

$$TDI_{BC,summer} = \int_{t_{season:summer}} \left[\left(T_{O,MAX-seas} + 3\right) - T_{O,MAX-seas}\right] d\tau + = 3 \cdot t_{seas:summer} \quad [K \cdot h] \tag{4}$$

$$TDI_{BC,winter} = \int_{t_{season:winter}} \left[\left(T_{O,MAX-seas} + 3\right) - T_{O,MAX-seas}\right] d\tau + = 3 \cdot t_{seas:winter} \quad [K \cdot h] \tag{5}$$

$TDI_{BC,seas}$ is the arbitrary base case scenario represented by a constant operative indoor temperature 3K far from each seasonal target (Figure 1).

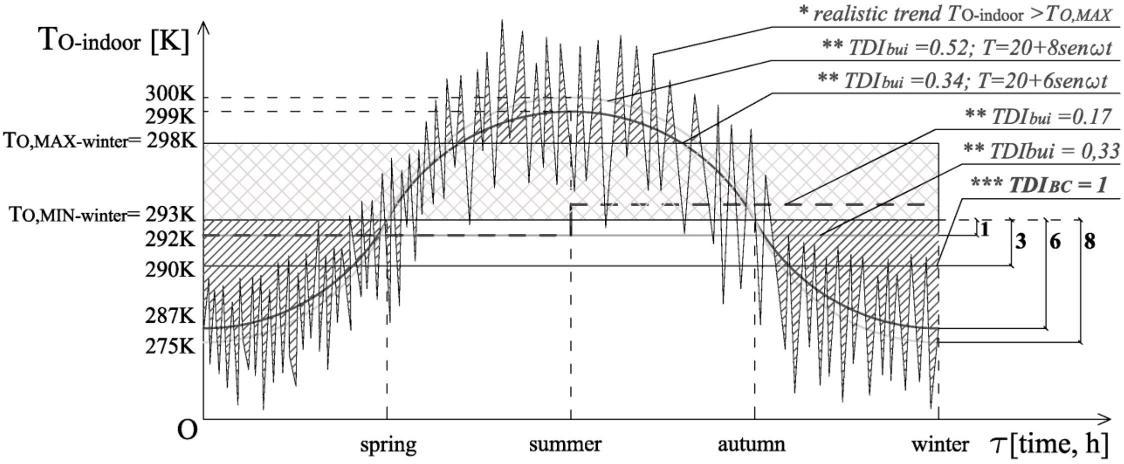


Figure 1. TDI_{bui}, TDI_{BC} realistic*, reference and base case*** scheme**

The second member of the product in (1) is a weighting factor always comprised between 0 and 1. This expresses the frequency of the $T_{O\text{-}indoor}$ distance from the indoor seasonal thermal target. Obviously all the structures that register a frequent and intense deviation far from the target are characterized by an high value of $TDI_{building}$ obtained both for an important deviation far from the thermal target (first member of the product) and for a frequent deviation (second member of the product close to unitary value).

A zero value of $TDI_{building}$ represents the final aim to pursue with all kinds of design strategies. Indeed it indicates that the thermal zone is characterized by $T_{O\text{-}indoor}$ always inside the thermal target. A value of $TDI_{building}$ higher than the unity means that the thermal zone is far from the target more than the base case scenario is. And obviously a bigger value of $TDI_{building}$ represents a bigger distance from the target.

3.2 Building thermal performance and climatic context: $TDI_{building\text{-}site}$

The proposed methodology comprehends also the analysis of the climate, that allows to evaluate buildings thermal performance also in relation to climatic context. The final aim of this phase is to evaluate $TDI_{building\text{-}site}$ for defining the building behavior normalized with respect to the weather site stress, also characterized by TDI_{site} index.

This procedure is important to avoid possible misunderstandings that often lead to judge a building performance better than another one located in a different climatic context, just because maybe in the first site the climate is less severe than the second place. So the climatic context is evaluated with a TDI_{site} index to quantify the stresses that should be dealt with a precise design process.

In this study three different locations in Italy are considered for the same prototypes: Palermo in the south of Italy, Perugia in the center and Bolzano in the north. Each city is characterized by a different value of TDI_{site} index typical of a seasonal or an annual period. The index expressed in the equation (6) is measured in [K·h].

$$IDT_{site,seas} = \left\{ \int_{P_{hot}-site} \left[f\left(T_{air\text{-}sun,site}\right) - T_{MAX\text{-}seas,site} \right] d\tau + \int_{P_{cold}-site} \left[T_{MIN\text{-}seas,site} - f\left(T_{air\text{-}sun,site}\right) \right] d\tau \right\} \cdot \frac{t_{seas} - t_{Target\text{-}site,seas}}{t_{seas}} \quad [K \cdot h] \qquad (6)$$

Where:
$T_{air\text{-}sun,\ site}$ is the location air sun temperature calculated on a reference horizontal surface;
$T_{MAX\ seas,\ site}$ and $T_{MIN\ seas,\ site}$ are the extreme values of the thermal ranges, expressed by $T_{air\text{-}sun,site}$. This reference thermal range is obtained as an extension of the internal target range on the hotter and colder temperature for 3K. So they are:
$T_{MAX\ summer,\ site}$ = 299K+3K = 302K e $T_{MIN\ summer,\ site}$=296K-3K = 293K;
$T_{MAX\ winter,\ site}$=298K+3K = 301K e $T_{MIN\ winter,\ site}$=293K-3K = 290K.
Then the following step consists of the calculation of the complex index $IDT_{bui,\ site}$ (7, 8) to define the building global performance freely from the location climate features. The analytical expressions are, respectively for the seasonal period and for the annual one:

$$TDI_{bui\text{-}site,seas} = \frac{\left\{ \int_{P_{hot}-bui} \left[f\left(T_{O\text{-}indoor}\right) - T_{O,MAX\text{-}seas} \right] d\tau + \int_{P_{cold}-bui} \left[T_{O,MAX\text{-}seas} - f\left(T_{O\text{-}indoor}\right) \right] d\tau \right\} \cdot \frac{t_{seas} - t_{Target\text{-}bui,seas}}{t_{seas}}}{\left\{ \int_{P_{hot}-site} \left[f\left(T_{air\text{-}sun,site}\right) - T_{MAX\,seas,site} \right] d\tau + \int_{P_{cold}-site} \left[T_{MIN\,stag,site} - f\left(T_{air\text{-}sun,site}\right) \right] d\tau \right\} \cdot \frac{t_{seas} - t_{Target\text{-}site,seas}}{t_{seas}}} \quad [-] \qquad (7)$$

$$TDI_{bui\text{-}site,\ year} = \sum_{i} IDT_{bui\text{-}site,seas\text{-}i} \cdot \frac{t_{seas\text{-}i}}{t_{year}} \quad [-] \qquad (8)$$

Where $P_{hot\text{-}site}$ and $P_{cold\text{-}site}$ typical of the location are the time periods during which the $T_{air\text{-}sun,\ site}$ is external to the thermal target range. So they are analytically expressed in (9) and (10).

$$P_{hot-site} = \left\{ \tau \in \left[0, t_{season}\right] : f\left(T_{air-sun,site}\right) \geq T_{MAX-seas,site} \right\} \quad [h] \qquad (9)$$

$$P_{cold-site} = \left\{ \tau \in \left[0, t_{season}\right] : f\left(T_{air-sun,site}\right) \leq T_{MIN-seas,site} \right\} \quad [h] \qquad (10)$$

These last indexes allowed to evaluate for example the real building performance also in comparison with another building in a different location, and it could be useful especially for existing buildings analysis.
A value equal to zero of the $TDI_{building\text{-}site}$ expresses the final aim to pursue, as for TDI_{bui}. The more the values of $TDI_{building\text{-}site}$ are far from zero, the more the thermal zone registers thermal conditions far from the target. At the same time TDI_{site} high values correspond to a severe climatic context and vice versa. In this way an indoor condition far from the target could correspond to a low quality of the thermal design or to a very severe climatic context that it is necessary to take into account for example when two buildings in different locations are compared.
The purpose of the work is to show how this methodology could guide researchers and designers to study: the global thermal performance of new and existing buildings, every optimization strategy effectiveness etc., all in relation to the specific context.

4. Case studies

In this section the three residential buildings representing the case studies are described and the proposed methodology is applied first to assess architectural shape influence. Later sensitivity analysis are conducted to study some important envelope features role on building energy performance.

4.1 Residential buildings modeling description

The three buildings presented are different for architectural layout, windows position and orientation. As described in Figure 2 and Table 1, they have the same plan area and the same transparent area in each thermal zone, that are: bedrooms, living-room and access-room. All the envelope elements have the same insulation level, mass and superficial optical properties.

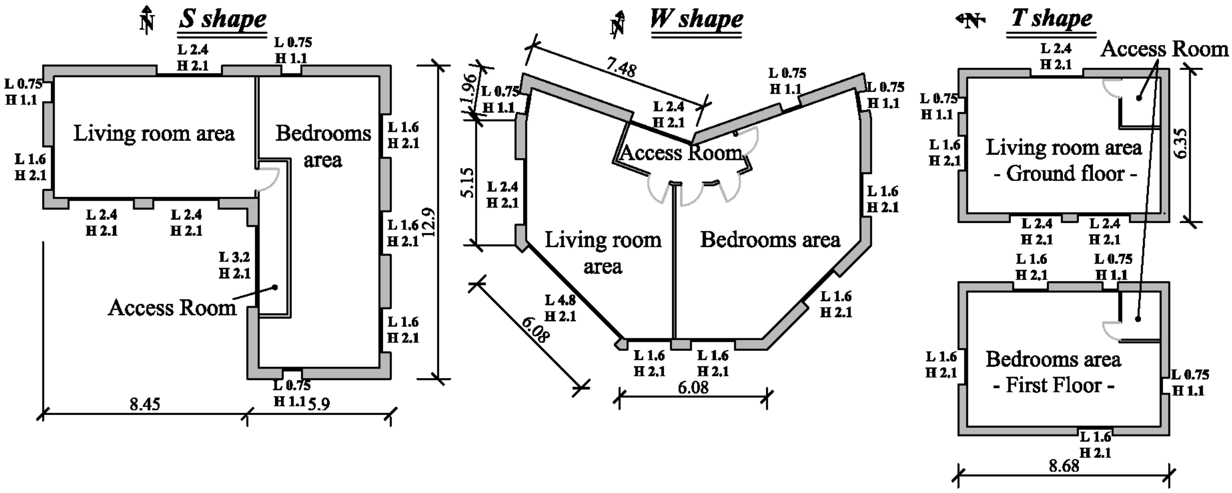


Figure 2. Prototypes plans, quote expressed in meters

Table 1. Buildings prototypes data

Shape →	S shape	W shape	T shape
Total floor area [m^2]	110	108	112
Living room area [m^2]	45	44	51
External wall area	78	60.9	106.2
Windows Area	19	19	19.0
Bedrooms area [m^2]	57	57	51
External wall area	89	69	106
Windows Area	11	11	11
Access-room area [m^2]	8	7	10

The first building (L shape) is designed to optimize the comfort level during the summer period when the night zone shields the day block from natural solar radiation and overheating. The south façade allows to optimize winter solar gain from very inclined solar radiation and it minimizes the overheating during the summer considering the almost vertical solar radiation. The bedrooms area is thought to receive the maximum natural light during the morning (east orientation) and to dispose of the entered heat during all the rest of the day. This first prototype name in this paper will be "S", for summer.

The second building shape, "W" for winter, optimizes solar gain contributions through all the transparent elements exposed on south, south-east and south-west orientations.

The third prototype represents the Italian typical residential house for one family, with living-room on the first level and all the bedrooms on the second floor. It is design without particular attention paid to climate influence on indoor comfort. Its name is "T" for traditional.

All these case studies are characterized by an internal gains quote of 4 W/m^2 [37] and 0,3 vol/h for the natural infiltration constant rate.

4.2 Envelope characterization for sensitivity analysis

The proposed methodology is applied also to define building performance in particular considering envelope properties. So selected features represent the input parameters IP while performing building simulations as a multi-variable optimization problem.
Sensitivity analysis allows to identify which variables are more important (high sensitivity) than others, and so where optimization strategies could be more effective from both technical and economical points of view. The proposed index TDI_{bui} is particularly effective for this field evaluations because it could be chosen as the output parameter OP for defining sensitivity coefficients SC.
TDI_{bui} output results represent a multivariable function (11) depending on different variables x_n concerning envelope, occupant indoor schedule, climate stresses, ventilation rates, energy plants features, etc.[4]. In this work sensitivity analysis regards some parameters of interest about envelope, as reported in (11):

$$TDI_{bui} = f(x_1; x_2; ...; x_n) = f(U_{env}; M_{env}; \rho_{roof}; ...; SHGC_{window}; \tau_{shad}) \quad (11)$$

Where the variables expressed, constituting the five IP of the sensitivity analysis, are:
U_{env}: opaque envelope transmittance measured in [W/m^{2}K];
M_{env}: opaque envelope mass. It is expressed in terms of internal thermal capacity, calculated according to [33] and measured in [kJ/m^{2}K];
ρ_{roof}: roof external surface reflectance, calculated according to [29]. It is a non-dimensional parameter variable between 0 and 1;
$SHGC_{wi}$: Solar Heat Gain Coefficient about windows glasses, calculated in the transparent area center. It is non-dimensional and comprised between 0 and 1;
τ_{shad}: diffusive venetian blinds transmittance optical property, calculated for ultraviolet, visible and near infrared wavelengths, following [38].
The differential of TDI_{bui} is calculated in (12):

$$dTDI_{bui} = \frac{\partial TDI_{bui}}{\partial U_{env}} dU_{env} + \frac{\partial TDI_{bui}}{\partial M_{env}} dM_{env} + \frac{\partial TDI_{bui}}{\partial \rho_{roof}} d\rho_{roof} + ... + \frac{\partial TDI_{bui}}{\partial SHGC_{wi}} dSHGC_{wi} + \frac{\partial TDI_{bui}}{\partial \tau_{shad}} d\tau_{shad} \quad (12)$$

The gradient of TDI_{bui} function for the first evaluated parameter U_{env} is (13):

$$\frac{dTDI_{bui}}{dU_{env}} = \frac{\partial TDI_{bui}}{\partial U_{env}} + \frac{\partial TDI_{bui}}{\partial M_{env}} \cdot \frac{dM_{env}}{dU_{env}} + \frac{\partial TDI_{bui}}{\partial \rho_{roof}} \cdot \frac{d\rho_{roof}}{dU_{env}} + ... + \frac{\partial TDI_{bui}}{\partial SHGC_{wi}} \cdot \frac{dSHGC_{wi}}{dU_{env}} \quad (13)$$

Considering that each IP variable is independent from every other one, then:

$$\frac{dM_{env}}{dU_{env}} = \frac{d\rho_{roof}}{dU_{env}} = ... = \frac{dSHGC_{wi}}{dU_{env}} = 0 \quad (14)$$

And then:

$$\frac{dTDI_{bui}}{dU_{env}} = \frac{\partial TDI_{bui}}{\partial U_{env}}; \frac{dTDI_{bui}}{dM_{env}} = \frac{\partial TDI_{bui}}{\partial M_{env}}; \frac{dTDI_{bui}}{d\rho_{roof}} = \frac{\partial TDI_{bui}}{\partial \rho_{roof}}; \frac{dTDI_{bui}}{dSHGC_{wi}} = \frac{\partial TDI_{bui}}{\partial SHGC_{wi}} \quad (15)$$

So the sensitivity analysis techniques can be applied to our problem with the aim of minimizing the objective function TDI_{bui} with respect to the considered design variables.

In this work the sensitivity analysis techniques are applied to study the different design strategies on "W" building shape, for all the three different Italian climates. Every simulation is conducted varying One parameter At a Time (OAT-method). The variability ranges are decided considering Italian typical residential buildings and the range extremes express the usual commercial availability of envelope products and materials. In particular Table 2 shows the variability of the IP variables and so the corresponding modelled buildings.
The Sensitivity Coefficient SC_i expressing every i-th IP role is obtained with (16), considering the maximum OP situation as the base case:

$$SC_i = \frac{\frac{OP_{max,i} - OP_{min,i}}{OP_{max,i}}}{\frac{IP_{max,i} - IP_{min,i}}{IP_{max,i}}} \quad [-] \tag{16}$$

Where $OP_{max,i}$ and $OP_{min,i}$ respectively are maximum and minimum values of the output parameters for each i-th considered design parameter IP. $IP_{max,i}$ and $IP_{min,i}$ respectively are maximum and minimum values of the "i" envelope input features.

Table 2 Input Parameters variability considered in sensitivity analysis

Levels → *Input Parameters ↓*	Low	Medium	High	Very High
External wall thermal capacity [kJ/m^2K]	wall: 60 roof: 44 floor: 56.5	wall: 110 roof: 85 floor: 107	wall: 160 roof: 126 floor: 157.5	wall: 210 roof: 167 floor: 208
Roof Reflectance [%]	22%	44%	66%	88%
Envelope Transmittance [W/m^2K]	0.16	0.5	0.84	1.19
$SHGC_{windows}$ [-]	0.22	0.42	0.62	0.82
Shieldings Transmittance [%]	20%	40%	60%	80%

4.3 Experimental activity on envelope materials

Experimental activity is carried out to realistically represent buildings prototypes for sensitivity analysis. In particular two important envelope properties are evaluated with in-field and in-lab measurements: roof reflectance and external walls transmittance.
Roof reflectance is measured on brick specimens obtained from traditional tiles largely diffused in Italian houses. The test method procedures described in ASTM E 903-96 [29] comprehends measurements of spectral near normal-hemispherical reflectance over the spectral range 300-2500 nm by an integrating sphere spectrophotometer. The solar reflectance value is obtained calculating a weighted average following the [30] prescriptions. This standard provides terrestrial solar irradiance distributions and so it is possible to deduce the reference spectra characterized by three uniform wavelength intervals (of 0.5 nm below 400 nm; 1 nm in 400÷1700 nm; 1702 nm value; 5 nm in 1705÷4000 nm) [30]. The used spectrophotometer is a *SolidSpec-3700* (Figure 3) produced by Shimadzu with a 60 mm of diameter integrating sphere. It has a 240-2600 nm spectral wavelength range; the working scheme is double beam in time and coated optics; the wavelength accuracy is more than 0.1 nm.

Figure 3 (a-b). ***SolidSpec-3700*** **spectrophotometer and specimen positioning.**

After recording the spectral 100% and the zero lines, the specimens of four different tiles are tested. The solar reflectance weighted value is calculated as follows [29]:

$$\rho_S = \frac{\sum_{i=1}^{n} \rho(\lambda_i) \cdot E_{\lambda i} \cdot \Delta\lambda_i}{\sum_{i=1}^{n} E_{\lambda i} \cdot \Delta\lambda_i} \quad [-] \qquad (17)$$

Where: $\rho(\lambda_i)$ is the spectral reflectance at wavelength λ_i; $E_{\lambda i}$ is the standard spectral irradiance distribution [30] at wavelength λ_i; $\Delta\lambda_i$ are the not constant wavelength intervals, and they are calculated as follows for every i-th interval [29]:

$$\Delta\lambda_i = \frac{\lambda_{i+1} - \lambda_{i-1}}{2} \quad [nm] \qquad (18)$$

Following the standards [29,30] for all the procedures of measurements and results post-processing, uncertainties and precision assessments are considered agreeing to the above reference standard. The tiles choice comprehends four types of pigment finishing mostly diffused in Italy, shown in Figure 4: natural dark brown ("Very Low R", Table 2), typical natural brick red ("Low R", Table 2), sand color ("Medium R", Table 2), titanium bioxide white coating ("High R", Table 2). Four specimens for every tile are obtained to calculate the tile reflectance as the average value of the four samples. The obtained reflectance values for sensitivity analysis are described in Figure 5 and reported in Table 2.

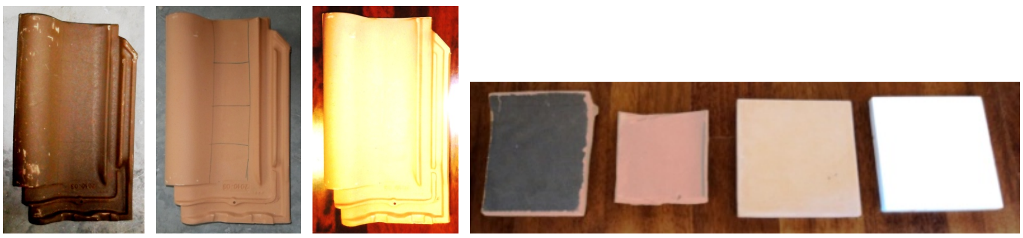


Figure 4 (a-b-c-d). Original tested tiles and four obtained specimens.

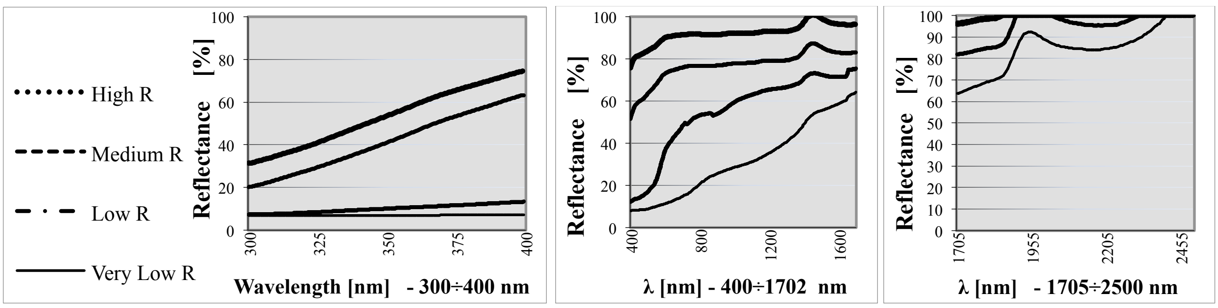


Figure 5 (a-b-c). ρ(λ) trends of the four tested specimens, for each uniform wavelength interval (high R: 88%, medium R:66%, low R: 44%, very low R: 22%; see Table 2).

The second envelope property characterized by experimental activity is external walls insulation level measured by transmittance. In this case the extreme values of the four cases examined are: a new Italian house, built on 2009 and classified in the best energy efficiency category ("Very Low U", Table 2); a traditional Italian house without any insulation panel, built on 1973, before every energy efficiency law issuing in Italy ("High U", Table 2). The two intermediate values ("Medium U" and "Low U", Table 2) comprised between the two extremes are directly designed in the simulation environment.
The transmittance measurements are conducted following the average method reported in ISO 9869:1994 [33]. The measurements accuracy evaluation and the error related to this procedures is considered according to the reference standard [33]. The used heat flowmeter (HFM) apparatus *Optivelox Thermozig* consists of: four temperature sensors (two on both internal and external side of the wall); one resistive plate for heat flux density measuring disposed on the wall internal side, to avoid the solar direct radiation and all meteorological phenomena disturb. All these sensors are connected to a datalogger and to a processor consisting of a classical PC.
The instrument parts are installed and positioned following the international standard [33] prescriptions to obtain the most realistic values (Figure 6). To avoid that test area could be affected by discontinuity and heterogeneity and to ensure that results could be representative of the whole element, before the beginning of transmittance measurements, the walls were observed using thermography techniques by *Flir B360*, according with ISO 6781 [39] as shown in Figure 7.

Figure 6 (a-b-c-d). HFM sensors positioning on internal side (a-b) and external side (c-d) of the house wall.

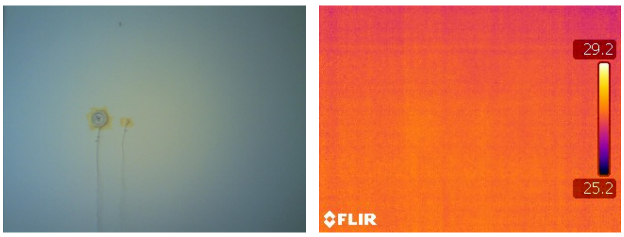


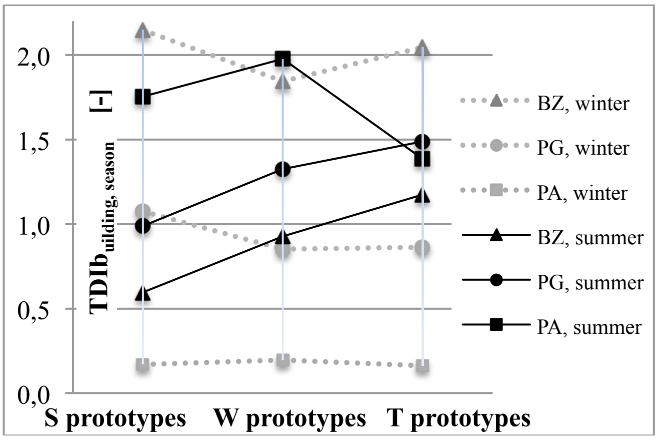
Figure 7 (a-b). Digital image and thermography of the tested wall (internal side).

5. Discussion of the results

This section regards the proposed methodology application to the case studies for evaluating architectural shape role compared to the climate context and the considered envelope features sensitivity. Finally the results expressed by TDI are compared to other common thermal quality indicators like Primary Energy consumption and Degree Hours Criteria [13].

5.1 TDI index for evaluating the interaction between architectural shape and climate

As shown in Figure 8 (a-b) the only modification of the architectural layout causes important TDI_{bui} variations. In particular the proposed method could be suitable to define the best building shape in relation to specific climate condition. Figure 8 also shows that the most important architecture influence occurs during summer, when climate is much more mild than the severe winter conditions in the three considered cities. TDI_{site} index allows to define the climate strength (Table 3). During the typical Italian summer season, just the shielding systems, the correct orientation and the passive techniques in general are more effective to obtain indoor thermal quality. Many benefits are indeed obtained for S prototypes ("L" shape). On the contrary severe winter weather imposes air-conditioning activation to obtain and to maintain indoor thermal good performance in the most of cases.



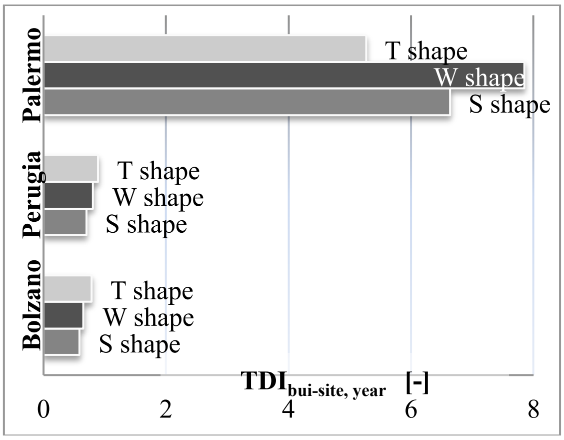


Figure 8 (a-b). (a): $TDI_{bui,seas}$ varying architectural layout, climatic location, seasonal period. (b): $TDI_{bui-site,}$year varying architectural layout and climatic location.

Table 3. Climate definition by TDI_{site} during seasonal and annual period

TDI_{site} [K·h]			
	Summer	Winter	Year
Bolzano	12638	51138	35000
Perugia	9790	40584	27676
Palermo	1240	13998	8650

As shown in Figure 8, the "L" shape (S prototype) has many benefits during summer except for the city of Palermo. The big solar load, typical of this site, provokes the upstairs floor overheating and it becomes an heat storage. On the contrary the ground floor seems cooled thanks to the second floor thermal capacity and this effect is not registered in the TDI_{bui} because it represents an average value between the living-room zone and the bedrooms zone.

During winter the W prototype optimizes the thermal quality, especially for the city of Bolzano, that is characterized by the most severe winter season, as shown in Table 3. The city of Palermo, having a very mild winter period, presents very few variation between different building layouts in this period.

The definition of $TDI_{bui-site}$ for the annual analysis allows to define the best architectural configuration for every site. For both the coldest cities (Bolzano and Perugia) the shape effect is less important than Palermo and the worse configuration is the Traditional one (duplex house). For the city of Palermo (Sicily), the typical mild climate of this Italian region underlines the importance of all passive techniques for defining the indoor thermal high performance. This particular climate leads to define the "T-shape" as the best one, for the reason explained above.

5.2 TDI index to express envelope features sensitivity

Now the proposed methodology is applied to evaluate some important envelope properties sensitivity. The results showed in Figures 9 and 10 and Table 4 regard the W prototypes located in Perugia.

Both for winter and summer analysis the windows properties have the most important role. Shading system transmittance and glasses SHGC cause the biggest OP variation with an almost linear trend during winter. The envelope transmittance typical trends, both on winter and summer, allow to define the optimum U value for Perugia. So this basic results coupling could guide also the design process and cost-benefit analysis. On the contrary the external wall inertia causes small TDI_{bui} variations but all over the year the high thermal capacity is more desirable. It is also important to note that the roof reflectance role is more important during summer almost causing an OP doubling between 0.9 and 1.6; this property presents the same linear trend also during winter, with a smaller effect, typical of winter analysis for all the reasons showed above.

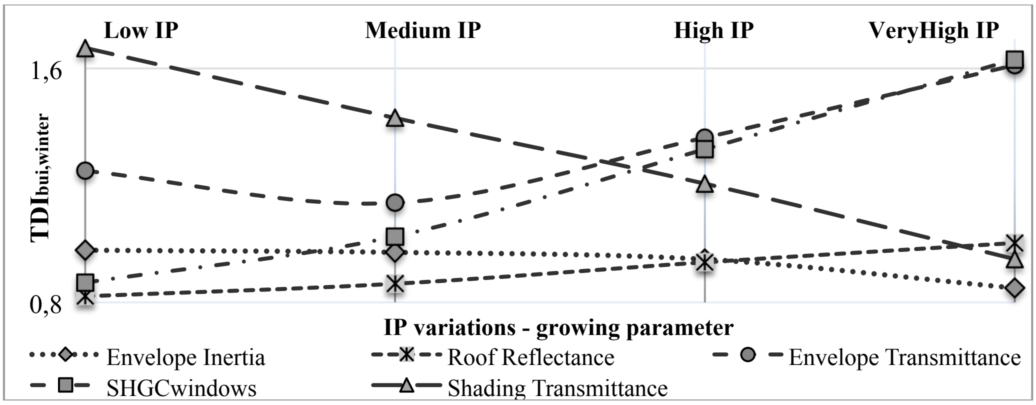


Figure 9. Sensitivity analysis results for the city of Perugia during winter period

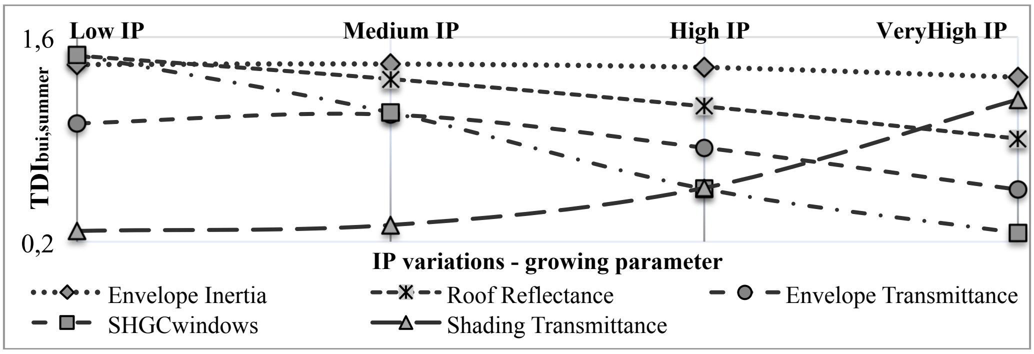


Figure 10. Sensitivity analysis results for the city of Perugia during summer period

Table 4. Sensitivity coefficients varying IP and climatic context for the W-shape

Sensitivity Coefficients (16) →	WINTER			SUMMER		
Input Parameters ↓	*Bolzano*	*Perugia*	*Palermo*	*Bolzano*	*Perugia*	*Palermo*
External wall Inertia	0,1159	0,1754	0,3876	0,0281	0,0848	0,2072
Roof Reflectance	0,1637	0,2429	0,1842	0,6729	0,5139	0,3457
Envelope Transmittance	0,3178	0,3898	0,3771	0,7588	0,6395	0,4799
$SHGC_{windows}$	0,4343	0,6241	0,4750	1,1577	1,0999	0,9564
Shieldings Transmittance	0,3896	0,5765	0,7500	0,9456	1,0204	0,9737

6. Correlation between TDI_{bui} and comfort index

To evaluate the relationship between the proposed index and other common thermal performance indicators, now the correlation between TDI_{bui} and an adaptive comfort criteria [13] is studied. The adaptive comfort indicator is represented by Degree Hours [K·h] index, used in [13] for long term evaluation of the general indoor thermal comfort conditions. Degree Hours (DH) values are calculated with the same climatic conditions [40] considered for dynamic simulations by [17], assuming a "II building category", explained in [13] as "Normal level of expectation and should be used for new buildings and renovations". As regards Perugia climate the correlation between TDI_{bui} matrix and DH matrix is calculated for both the seasons, varying the envelope transmittance, inertia and reflectance in the same way presented for sensitivity analysis (Table 2).

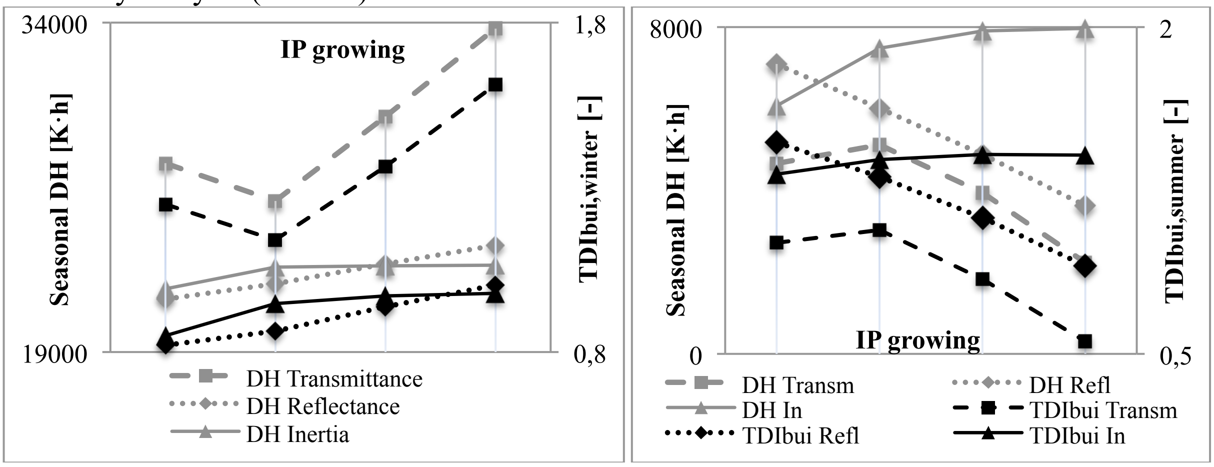


Figure 11 (a-b). Correlated TDI_{bui} and DH values varying envelope IP (Transmittance, Reflectance, Inertia) for winter (a) and summer (b).

As shown in Figure 11 the proposed $TDI_{bui,seas}$ could be representative of the thermal comfort indicator Degree Hours, both on winter and summer. Indeed the correlation coefficients values are 99.62% for winter and 96.15% for summer.

7. Conclusions

In this study a methodology for building thermal performance evaluation coming from dynamic simulation is proposed and applied to different case studies. So three Italian residential houses prototypes are simulated in a dynamic environment also considering the results obtained from experimental measurements on real buildings. The method is applied to assess the architectural shape and passive techniques role, as well as some important influence of envelope features on thermal behavior both during winter and summer. It could also be applied both on preliminary building design stage and to support every energy improvement intervention on existing buildings in different climates.

The method comprehends a preliminary analysis and buildings dynamic modeling as the first step of the process. The results are organized to calculate thermal performance by concise but also exhaustive indexes called Thermal Deviation Indexes regarding the indoor buildings behavior also related to the real climate as a main boundary condition.

So the proposed methodology allowed to evaluate building performance according to different realistic climate conditions simulated. In this study three different Italian cities are considered: Bolzano in the north of Italy with a very cold weather, Perugia in central Italy characterized by intermediate conditions and Palermo in the south of Italy with typical mild Sicilian conditions.

The proposed method is then applied also to sensitivity analysis used to study different properties influence such as: envelope transmittance and thermal capacity, roof reflectance, glasses Solar Heat Gain Coefficient, shielding system solar transmittance. So it was possible to define which kind of intervention could be more effective than another also considering the cost-benefits perspective, for every climate, in every seasonal period.

The obtained results underline the main role of architectural shape and passive techniques especially regarding windows properties related to glasses solar transmittance and to shielding system design. The relative sensitivity coefficients are greater than those concerning opaque envelope by more than 50%. All these considered Input Parameters are evaluated for each climate location and season, obtaining the corresponding Sensitivity Coefficients values. In particular SC summer values are greater than the winter ones by more than 40% and the maximum sensitivity corresponds to $SHGC_{windows}$ for Perugia and Bolzano, and to shieldings transmittance for the city of Palermo

To evaluate if the proposed index could be representative of indoor thermal comfort, the TDI_{bui} results are then compared to another important index regarding adaptive comfort (Degree Hours index), obtaining a correlation coefficient above 96% for each season.

8. Nomenclature

T: Temperature [K]
$TDI_{building}$: Thermal Deviation Index referred to the building performance [-]
$TDI_{building-site}$: Thermal Deviation Index referred to the building in relation to the climate [-]
$T_{O-indoor}$: indoor thermal zone operative temperature [K]
$T_{O,MAX-seas}$; $T_{O,MIN-seas}$: indoor operative temperature target range limits [K]
t_{seas}; t_{year}: seasonal and annual analysis periods [h]
$t_{Target-bui,seas}$: period during which $T_{O-indoor}$ is in the thermal seasonal target [h]
$P_{hot-bui}$; $P_{cold-bui}$: periods during which $T_{O-indoor}$ is out of the seasonal thermal target [h]
$TDI_{BC,seas}$: Base Case Thermal Deviation Index [K·h]
TDI_{site}: Thermal Deviation Index typical of the climate location [K·h]
$T_{air-sun,\ site}$: air-sun temperature on a reference horizontal surface [K]
$T_{MAX\ seas,\ site}$ and $T_{MIN\ seas,\ site}$: air-sun temperature range limits [K]
$P_{hot-site}$; $P_{cold-site}$: periods during which $T_{air-sun,\ site}$ is out of the site seasonal thermal target [h]
OP; IP: output and input parameters of sensitivity analysis respectively [-]
$IP_{max,i}$; $IP_{min,i}$: input parameters extremes represented by envelope properties [various]
SC_i: sensitivity coefficient corresponding to every i-th input parameters [-]
$OP_{max,i}$; $OP_{min,i}$: output parameters extremes referred to the i-th input parameter IP [-]
U_{env}: opaque envelope transmittance [W/m^2K]
M_{env}: opaque envelope internal thermal capacity [kJ/m^2K]
ρ_{roof}: roof external surface reflectance [-]
$SHGC_{wi}$: Solar Heat Gain Coefficient about windows glasses [-]
τ_{shad}: diffusive venetian blinds transmittance optical property [-]
ρ_s: solar reflectance value [-]
$\rho(\lambda_i)$: spectral reflectance at wavelength λ_i [-]
$E_{\lambda i}$: standard spectral irradiance distribution at wavelength λ_i; [$W/(m^2nm)$]
$\Delta\lambda_i$: wavelength intervals delimited by $\Delta\lambda_{i-1}$ and $\Delta\lambda_{i+1}$ [nm]
DH: Degree Hours index, calculated with [15251], [K·h]

9. References

[1] Pachauri, R.K. and Reisinger, A., "Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change" IPCC, Geneva, Switzerland.
http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html
[2] Al-Homoud M.S., 1997, "Optimum Thermal Design of Air-Conditioned Residential Buildings", *Building and Environment*. Vol 32, No 3, pp. 203-210.
[3] Ghiaius C., 2003, "Free-running building temperature and HVAC climatic suitability", *Energy and Buildings*, Vol 1, No 35, pp.405-411.
[4] Lam J.C., Hui Sam C.M., 1996, "Sensitivity Analysis of Energy Performance of Office Buildings", *Building and Environment*, Vol 31, No 1, January, 1996, pp. 27-39.
[5] Jiang H., Akira H., Takashi A., 2009, "A numerical simulation tool for predicting the impact of outdoor thermal environment on building energy performance", *Applied Energy*, Vol 86, No 9, pp. 1596-1605.

[6] Fabrizio E., Corrado V., Filippi M., 2010, "A model to design and optimize multi-energy systems in buildings at the design concept stage", *Renewable Energy*,Vol 25,No 3, pp.644-655.
[7] Ochoa C.E., Capeluto I.G., "Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate", 2008, *Building and Environment*, Vol 43, No 11, pp. 1829-1839.
[8] Ylmaz Z., "Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate", 2007, *Energy and Buildings*, Vol 39, No 3, pp. 306-316.
[9] Bleil de Souza C., Knight I., "Thermal Performance simulation from an architectural design viewpoint", Proceedings of Building Simulation 2007, September 03-06, 2007, Beijing, China.
[10] Bouchlaghem N., 2000, "Optimising the design of building envelopes for thermal performance", *Automation in Construction*, Vol 10, No 1, pp. 101-112.
[11] Al-Homoud M.S., Degelman L., Boyer L.L., 1994, "The framework of an optimization model for the thermal design of building envelopes", Proceedings of Ninth Symposium on Improving Building Systems in Hot and Humid Climates, May 19-20,1994, Texas.
[12] Corgnati S.P., Fabrizio E., Filippi M., 2008, "The impact of indoor thermal conditions, system controls and building types on the building energy demand", *Energy and Buildings*, Vol 40, No 4, pp. 627-636.
[13] CEN EN 15251:2007, "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics".
[14] Olesen B. W., 2007, "The philosophy behind EN15251: Indoor environmental criteria for design and calculation of energy performance of buildings", *Energy and Buildings*, Vol 39, No 7, pp. 740-749.
[15] Peeters L., Dear R., Hensen J., D'haeseleer W., 2009, "Thermal comfort in residential buildings: Comfort values and scales for building energy simulation", *Applied Energy*, Vol 86, No 5, pp. 772-780.
[16] Roetzel A., Tsangrassoulis A., Dietrich U., Busching S., 2010, "On the influence of building design, occupants and heat waves on comfort and greenhouse gas emissions in naturally ventilated offices. A study based on the EN 15251 adaptive thermal comfort model in Athens, Greece", *Building Simulation*, Vol 3, No 2, pp. 87 – 103.
[17] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Building Technologies Program: EnergyPlus.
[18] Crawley D.B., Lawrie L.K., Winkelmann F.C., Buhl W.F., Huang Y.J., Pedersen Curtis O., Strand R.K., Liesen R.J., Fisher D.E., Witte M.J., Glazer J., "EnergyPlus: creating a new-generation building energy simulation program", 2001, *Energy and Buildings*, Vol 33, No 4, pp. 319-331.
[19] Crawley D.B., Hand J.W., Kummert M., Griffith B.T., "Contrasting the capabilities of building energy performance simulation programs", 2008, *Building and Environment*, Vol 43, No 4, pp. 661-673.
[20] Zhai Zhiqiang J., Chen Qingyan Y., 2008, "Sensitivity analysis and application guides for integrated building energy and CFD simulation", *Energy and Buildings*, Vol 38, No 9, pp. 1060-1068.
[21] Zhu Y., Xia C., Lin B., 2007, "Discussion on methodology of applying building thermal simulation in conceptual design", Proceedings of Building Simulation 2007, September 03-06, 2007, Beijing, China.
[22] Heiselberg P., Brohus H., Hesselholt A., Rasmussen H., Seinre E., Thomas S., 2009, "Application of sensitivity analysis in design of sustainable buildings", *Renewable Energy*, Vol 34, No 9, pp. 2030-2036.
[23] Mara T.A., Tarantola S., 2008, "Application of global sensitivity analysis of model output to building thermal simulations", *Building Simulation*, Vol 1, No 4, pp. 290 – 302.

[24] Di Perna C., Stazi F., Casalena A. Ursini, D'Orazio M., 2011, "Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads", *Energy and Buildings*, Vol 43, No 1, pp. 200-206.
[25] Ascione F., Bellia L., Mazzei P., Minichiello F., 2010, "Solar gain and building envelope: the surface factor", *Building Research and Information*, Vol 2, No 38, pp. 187-205.
[26] Iqbal I., Al-Homoud M.S., 2007, "Parametric analysis of alternative energy conservation measures in an office building in hot and humid climate". Building and Environment, Vol 42, No 5, pp. 2166-2177.
[27] Synnefa A., Santamouris M., Apostolakis K., 2007, "On the development, optical properties and thermal performance of cool colored coatings for the urban environment", *Solar Energy*, Vol 81, No 4, pp. 488-497.
[28] Parker D.S., Barkaszi Jr S.F., 1997, "Roof solar reflectance and cooling energy use: field research results from Florida", *Energy and Buildings*, Vol 25, No 2, pp. 105-115.
[29] ASTM E 903-96, "Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres".
[30] ASTM G 173-03, "Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface".
[31] Levinson R., Akbari H., Berdahl P., 2010, "Measuring solar reflectance—Part I: Defining a metric that accurately predicts solar heat gain", *Solar Energy*, Vol 84, No 9, pp. 1717-1744.
[32] Levinson R., Akbari H., Berdahl P., 2010, "Measuring solar reflectance—Part II: Review of practical methods", *Solar Energy*, Vol 84, No 9, pp. 1745-1759.
[33] ISO 9869:1994, "Thermal insulation – Building elements - In-situ measurement of thermal resistance and thermal transmittance".
[34] Yilmaz Z., 2007, "Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate", *Energy and Buildings*, Vol 39, No 3, pp. 306-316
[35] Decreto Legislativo 29 dicembre 2006, n. 311, "Disposizioni correttive ed integrative al decreto legislativo 19 agosto 2005, n. 192, recante attuazione della direttiva 2002/91/CE, relativa al rendimento energetico nell'edilizia" (in Italian), Gazzetta Ufficiale n. 26, February 1,2007.
[36] KlimaHaus Agentur GmbH, 2010, "Direttiva tecnica CasaClima", http://www.zero-emissionplatform.eu/website/
[37] Cotana F, Pisello A.L., 2010, "Sul comportamento termico di edifici residenziali al variare della configurazione architettonica" (in Italian), Proceedings of ATI Conference, September 13-17, Cagliari, Italy.
[38] ISO 15099:2003, "Thermal performance of windows, doors and shading devices -- Detailed calculations".
[39] ISO 6781:1983, "Thermal insulation - Qualitative detection of thermal irregularities in building envelopes - Infrared method".
[40] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Building Technologies Program.
http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=6_europe_wmo_region_6/country=ITA/cname=Italy. WMO Station Region 6 : Italy, Perugia 161810 (IGDG); Bolzano160200 (IGDG); Palermo 164050 (IWEC).