Chapter 25
Assessing Optimal *U*-value in Residential Buildings in Temperate Climate Conditions Considering Massive Dynamic Simulation and Statistical Uncertainty

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Nomenclature

BIM	Building information modelling
CNV	Control natural ventilation
EAM	Energy analysis model
RMSE	Root mean square error

Introduction

The need to reduce energy consumptions as well as the relevant GHG emissions in the building sector without reducing comfort conditions is an essential aspect of current European and international regulations [1]. The building sector is, in fact, responsible for about 40% of total primary energy consumption [2–4], with space heating, cooling, and ventilation as an essential part of this percentage [5]. While adopting strict regulations at European and national level to reduce the heating energy needs, the energy need for cooling is growing worldwide since the past

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decades due to several causes including global warming, international style of buildings, and improvements in comfort expectations [6, 7]. So it is important to start considering not only the reduction in heating energy needs, but also cooling energy needs in balancing sustainable design choices between these two aspects to prevent summer overheating [8, 9]. In some cases, in fact, specific choices to increase solar heating gains and prevent thermal losses (e.g., high insulation levels), may negatively affect summer seasonal performances [9–11]. Fortunately, technologies have been improved and several methods are proposed for energy need optimization [12]. For example, in the ICT field, to manage the energy in residential buildings effectively, several efficient energy control systems have been developed, capable of decreasing the total energy need without compromising the user-preferred environment inside the building—see, for example, the results of EU project such as SeemPubs or DIMMER [13]. Nevertheless, a lack of approaches to consider all these aspects in building design, since early-design phases, is evident, especially when hourly simulation analyses are needed (e.g., for passive solutions) being the simplified monthly and steady state methods not sufficiently reliable in all cases [9, 14]. Some previous approaches were studied for environmental and technological design, based on simplified tools derived by advanced simulation and testing results—e.g., see the approach to calculate the wind wake core (wind shade core) proposed in [15]—allowing to include since early design the potential effect of design choices on the expected energy needs and environmental performances. Nevertheless, a full application of the potential of using the results of massive dynamic simulations driven by scripts and analyses using statistical and genetic optimization tools was suggested—see also [16, 17]—, but is still far to be fully applied, even if recent studies have demonstrated the potential of these approaches [18, 19]. Nevertheless, recent analyses were conducted by the authors and some early result was published [20, 21]. Therefore, this paper has been done in order to model the relationships between thermal insulation of the residential building stock envelope, i.e., walls and windows, and the energy needs for both space heating and cooling, to correlate these aspects by also considering a simple economic evaluation to optimize this variable including energy and economic aspects. Furthermore, natural cooling solutions, such as natural controlled ventilation, were also included in this analysis.

This paper follows the environmental building programming approach—see, for example, the description in [22]—which is based on the performance-driven methodology that suggests, since its early definition, the usage of algorithms and programs to optimize building performances [23, 24].

Hence, the analysis presented in this paper is about the developing of an algorithm with the aim of optimizing, through dynamic energy simulation, the energy and technological definition of a building envelope—focusing on the insulation layer—, such that the energy needed in a residential building can be minimized by also considering the related economic impact. The analysis has been carried out taking into account not only the heating season, such as it is generally done in regulations for the definition of minimal insulation values, but also the summer season.

This study is strongly innovative introducing a new approach to dynamic simulation usage for design purposes, thanks to the development of specific scripting procedure to produce regression-based models to be easily used by professionals of the architectural fields.

Methodology

The aim of this analysis is to develop a method and a tool to define the best configuration of building vertical envelope elements (opaque and transparent) considering the thermal insulation requirement. This requirement is tested to minimize the energy needs (target variable) in a residential building, taking into account (input variables):

- Seasonally changing conditions (cooling and heating comfort thresholds)
- Presence/absence of ventilative cooling systems
- Orientation of the building with respect to the north direction
- Different design choices—window *U*-values and thickness of wall and roof insulation layer

Furthermore, the analysis also considers the effect of random occupancy variations to simulate the potential effect of internal gains changes in real environments and test statistically the obtained regression models by previous simulations conducted under reference occupancy schedules. Finally, an economic study was conducted to consider the costs of different insulation layers and the related effect on the predicted costs for space cooling and heating. This last analysis can be used to optimize the design choices in a NZEB vision including not only energy optimization, but also an economical one.

In order to optimize this variable, a large database of dynamic energy simulation results was produced by using *EnergyPlus*. To manage this activity, a support code in Python has been implemented to change dynamically the input file used by the program (∗*.idf*), varying some input variables that play a fundamental role in the envelope thermal design and affect the *U*-value. In particular, it changed the thickness of the insulation layer for opaque elements and a series of specific window systems for the transparent ones. In addition, on/off activation of the CNV (controlled natural ventilation) system were considered in summer to test the effect of this passive/low-energy cooling technique. The study has been performed for a residential building located in *Torino*, Italy (temperate climate conditions), assuming a sample residential unit of about 70 m^2. The apartment was considered as a two-person flat in accordance to suggestions by architects' manuals [25]—considering entrance, kitchen, bathroom, and two rooms, even if for the purpose of this analysis internal spaces are assumed at the same temperature and scheduling being a unique thermal zone. Figure 25.1 shows the position of the considered unit in a residential building assuming a critical condition where three vertical faces and the roof are exposed to the external environment. The remaining vertical face and the floor are assumed to confine with spaces at the same temperature and consequently no thermal changes are expected by these surfaces.

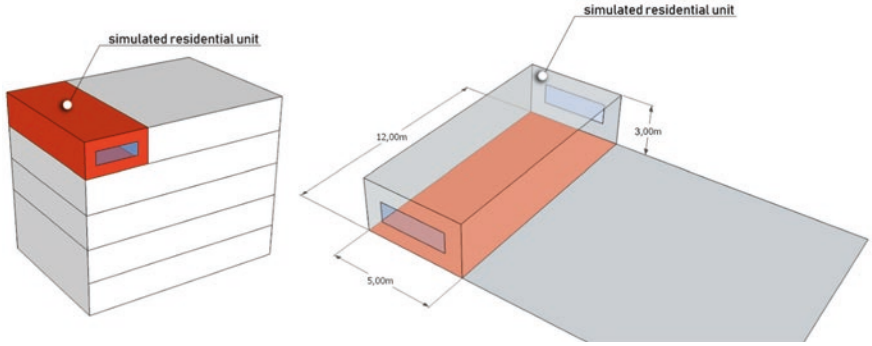

Fig. 25.1 The sample simulated residential unit and the considered sample building

Comfort threshold for system activation are assumed to be, respectively, 20 °C for winter and 26 °C for summer. Internal power density was assumed to be 10 W/m^2 in accordance to small office and residential unit suggestions [26]. Occupation schedule for the reference case was assumed to be the residential dwelling unit (with kitchen) by the ASHRAE database implemented in DesignBuilder.

In order to support the study development, the basic configuration was built in DesignBuilder and furthermore the EnergyPlus input file was changed via a Python script in order to generate large amount of simulations by changing the described input variables. Defined the models, by statistically analyzing the massive amount of produced results, uncertainty effects were added to test the ability of these polynomial regressions to face perturbation phenomena. In particular, a random variation of internal gains—i.e., occupancy—was introduced and statistical checking was performed to choose the best curves. Finally, a simple economic model was applied to obtain models to suggest the optimal points to be used by architects and designers in order to optimize, since early-design phases, the level of insulation in comparison to local boundary conditions considering a whole economic and energetic approach.

The following steps define the procedure used to reach the aim of this analysis:

- *Building reference model development*. Residential building development in DesignBuilder to export the first ∗.idf files for different situations of CNV (on/off), different orientations and considered types of window (see Table 25.1). Window *U*-values are in fact assumed according to commercial solutions for three typical configurations: single glass, double glass LoE Argon infilled, and triple glass LoE Argon infilled. As it is shown in Fig. 25.2a, the unit was defined to be 5 m in width, 12 m in length, and 3 m in height. The two shorter opposite facades have a window, while the other external vertical one is only opaque in accordance to the building typology. For this first step—DesignBuilder starting ∗idf. definition—the insulation layer was fixed equal to 0.0001 m—see Table 25.1 and wall and roof configurations in Fig. 25.2b, c—being further changed by the Python script. ∗.Idf files for each orientation of the building and for each season

Table 25.1 Simulation changed variables

Variable	Description	Value
Thickness of the insulating layer	Insulating layer composed by XPS extruded polystyrene	Variable value in the range {0,35} cm
U-value for different insulation thickness	Each thickness of insulation corresponds to a wall *U*-value and a roof *U*-value	Insulation thickness = 0.0001 m → wall *U*-value = 2.970 [W/m^2 K]; roof *U*-value = 1.539 [W/m^2 K] Insulation thickness = 0.35 m → wall *U*-value = 0.094 [W/m^2 K]; roof *U*-value = 0.091 [W/m^2 K]
Type of window's glass	Single Clr Double LoE Clr, Arg Triple LoE Clr, Arg	SHGC = 0.819; *U*-value = 5.778 SHGC = 0.568; *U*-value = 1.493 SHGC = 0.474; *U*-value = 0.780
CNV	Ventilative cooling producing air changing (naturally or fan-forced)	On/off On mode: 6 ac/h. operating ambient temperature thresholds in the range {18,24} °C, activation threshold difference (internal–external temperature) assumed to be equal to 3 K [27]
Occupancy	Average number of people per floor area	$\mu = 0.037$ [people/m^2] $\sigma = 0.0225$ [people/m^2]

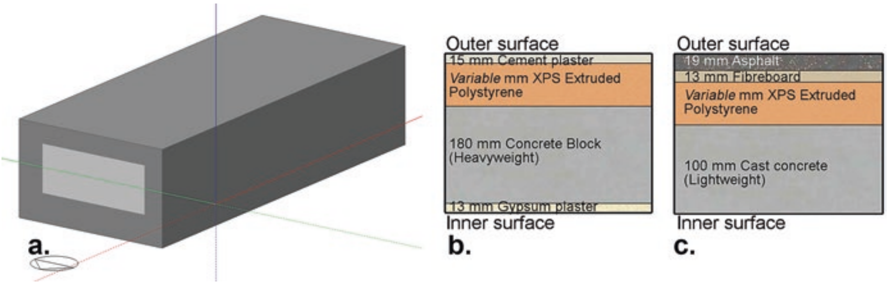

Fig. 25.2 (**a**) Design Builder's external view of the simulated unit. Three vertical walls and the roof are exposed to external conditions, while the last wall and the pavement are assumed as adiabatic, (**b**) configuration of wall layers, and (**c**) of roof layers. The insulation layer is the one whose thickness is automatically changed through the Python code

have been generated in DesignBuilder and further used as inputs for running EnergyPlus. Results are saved to be used in the analysis steps.

- *Python script implementation* to dynamically generate different ∗.idf input files for EnergyPlus by automatically varying the values of the thickness of the insulation layer of opaque surfaces which correspond to a *U*-value variation—see Table 25.1.
- *Python script development to* iteratively *run simulations* considering all ∗.idf files generated before. EnergyPlus obtained results are collected and data plotted in figures. The EnergyPlus run was done by setting, through the Eppy Python library, the ∗.idd file, the ∗.idf file, and the ∗.epw file in order to create

a link between Python simulations and the EnergyPlus software. The last file (∗.epw) is the one referring to local typical meteorological year for dynamic energy simulations and is assumed for this analysis by the EnergyPlus Weather Database.

- *Noise addition to test the effects of uncertainty phenomena on results*. The Python script was upgraded to add a noise contribution by changing, for each insulation thickness value, the average building occupancy following a Gaussian normal distribution with mean μ equal to two persons and an equal variance σ value, such that the occupancy may variate from 0 up to 4 average number of persons present in the building during the simulation. Nevertheless, the general time schedule was not changed. Occupancy average values are reported in Table 25.1.
- *Economic analysis* to evaluate how parameters variation influences the expected household expenditure and energy analysis to find the best combination in terms of potential energy saving.
- *Polynomial regressions* were performed in order to find the best fitting curve, which represents the energy need distribution, and evaluate the RMS (root mean square) error between curve points (model) and the simulated ones (test) using additional simulation runs.

The main considered input variable is hence represented by the U-value, which represents the thermal transmittance, and is the rate of transfer of heat through a structure divided by the difference in temperature across that structure [W/m^2 K]. This value is compatible, in the architectural technology design approach based on the performance-driven methodology, to requirement No. 39 of the UNI 8290-2: 1983. The U-values [W/m^2 K] of each window configuration used for simulations are defined in Table 25.1, such as was mentioned before, while the U-value of opaque surfaces can be deducted by the thickness of the insulation layer by using the well-known expression (25.1):

$$U_{\text{value}} = \frac{1}{\frac{1}{h_{\text{i}}} + \sum R + \sum \frac{s}{\lambda} + \frac{1}{h_{\text{e}}}} \tag{25.1}$$

where R is the thermal resistance of a layer [m^2 K/W], s is the thickness of a layer, and λ is its thermal conductivity [W/m K]—R or s/λ are used alternatively according to layer definition—$1/h_{\text{i}}$ and $1/h_{\text{e}}$ are, respectively, the surface resistances of the internal surface and the external one, which can be assumed to be 0.13 and 0.04 for horizontal flow (vertical opaque closures), 0.1 and 0.04 for ascending flow, and 0.17 and 0.04 for descending one in accordance to Italian regulations. Figure 25.3 compares the insulation thickness with the related U-values of the opaque vertical wall and the flat roof. The insulation thickness in the roof is assumed to be the same of the wall and consequently the two closures U-values vary accordingly even if the different configuration of the other layers causes a similar, but not equal U-value.

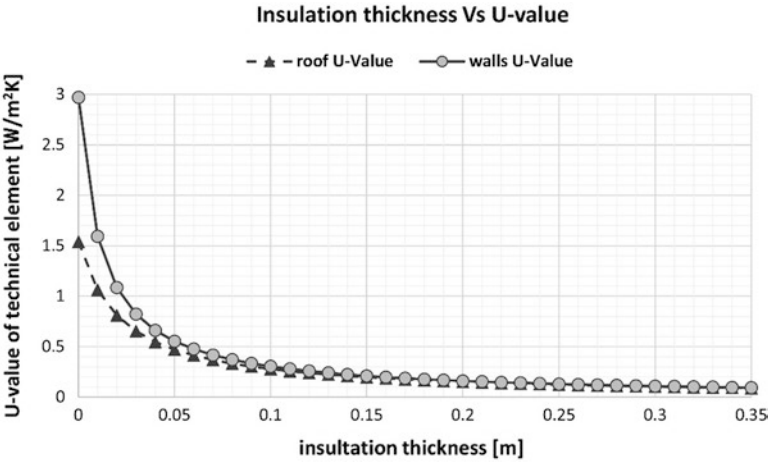

Fig. 25.3 Insulation thickness and related variation in the total *U*-value of the opaque vertical walls and horizontal roof

Analysis

It is known that by choosing a good orientation during the building design phases, combined with other energy efficiency features, it is possible to reduce or even eliminate (according to local climate conditions) the need for auxiliary heating and cooling, resulting in lower energy bills, reduced greenhouse gas emissions, and improved comfort conditions in free-running. Several studies were conducted on this specific aspect in different climate conditions, being one of the classic bioclimatic variables to be optimized according to the specific site [28–30]. For this reason, building orientation in respect to apparent local sun paths was considered relevant for the analysis—see Fig. 25.4a, b. For each orientation, the entire set of simulations was conducted in order to compare results and obtain potential information to be used as early-design strategies according to the chosen configuration. A total of 1296 simulations were run for the base occupation schedule and average number of people.

Winter Energy Needs

In this paragraph, the simulated winter energy needs are reported and discussed for the base case. Figure 25.5 shows the simulated unit behavior considering heating energy needs for different thickness of the insulation layer. Each graph refers to a specific building orientation, respectively with the large exposed opaque vertical closure facing North, Fig. 25.5a, facing East, Fig. 25.5b, facing West, Fig. 25.5c,

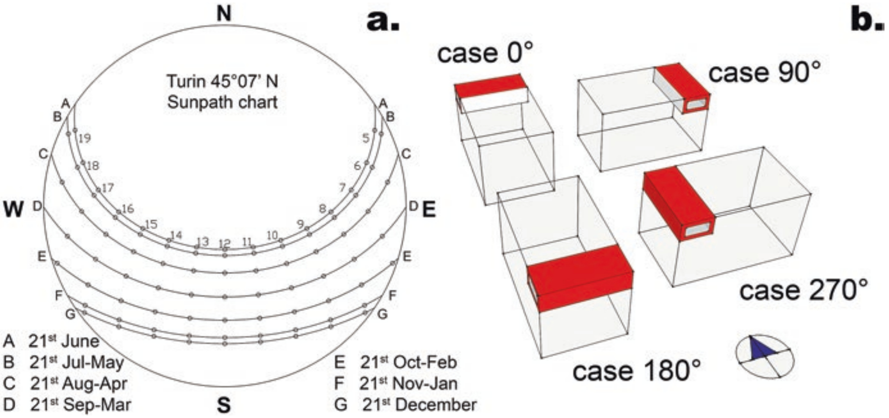

Fig. 25.4 (**a**) The sun paths during different seasons for the considered location; (**b**) chosen orientations of the simulated units (in red), note the orientation of the fully opaque wall exposed to the environment

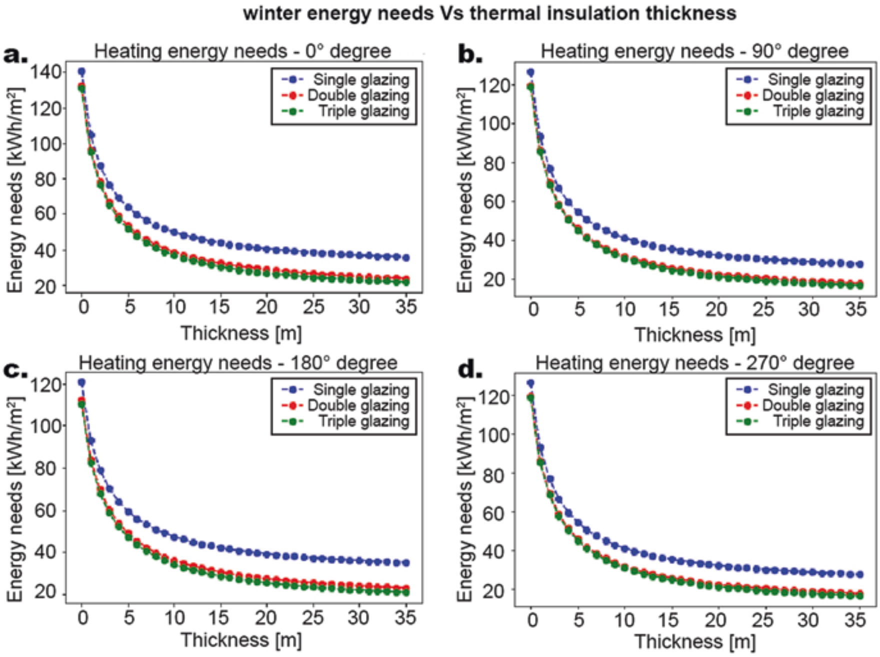

Fig. 25.5 Winter energy needs for the four considered orientations: (**a**) 0 degree—North direction of the long exposed façade (window orientation E–W), (**b**) 90 degrees (window orientation N–S), (**c**) 180 degrees, and (**d**) 270 degrees—see also Fig. 25.4b

Table 25.2 Average saved energy needs in winter—orientation degrees refer to the totally opaque façade confining with the external environment

	0° from North (kWh/m^2 year)	90° from North (kWh/m^2 year)	180° from North (kWh/m^2 year)	270° from North (kWh/m^2 year)
Single glass	100.78	79.34	100.96	79.26
Double glass	77.85	61.73	78.11	61.66
Triple glass	68.42	55.75	68.66	55.67

and facing South, Fig. 25.5d—see also Fig. 25.4b. Furthermore, the effect of the three considered window types is reported in each figure according to the reference line (single, double, and triple window cases). From this figure, it is possible to notice that similar trends in energy needs were obtained for all orientations and all considered window types. At the same time, the main contribute to the obtained energy saving is given by the increase of the insulation thickness (and correlated decrease in the walls *U*-values), while the orientation and the windows type add a smaller but visible alteration. More precisely, the greater effect of insulation is appreciable in the range 0–10 cm of thickness, according to the higher *U*-value variations—see Fig. 25.3.

The highest amount of heating energy needs for low insulation levels was reached by the north-oriented-long-façade case (windows facing E–W)—see Fig. 25.5a. This is an expected outcome, considering that, in winter, the East and West window orientations are interested by a lower intensity in solar gains in respect to the south-oriented one, while the difference in between cases (a) and (c) is due to the exposure of the external-facing wall to north orientation in respect to the south one. On the other hand, in fact, minor energy needs are achieved for the other building orientations. When the internal wall faces the south direction, Fig. 25.5c, the external-facing wall is passively heated by the sun during the whole day, while with orientation 90° and 270°, respectively Fig. 25.5b, c, one window is south-oriented. Furthermore, such as was expected, the higher the insulation thickness, the lower the energy need being a reduction in thermal losses through the envelope a positive strategy for reducing the heating needs. For this reason the minimal and maximal insulation levels were compared. The average saved energy needs applying an insulation layer of 35 cm in all considered orientations and types of glass in respect to the not insulated case are shown in Table 25.2 for the heating season, confirming the above described trends.

Summer Energy Needs (CNV Off)

The behavior of the energy consumption during summer season without ventilative cooling activation is shown in Fig. 25.6 for the same building orientations of Fig. 25.5, the same types of window and walls insulation thicknesses of the previous analysis.

Although from 1 to 35 cm the need variations are less evident than for the heating case, it is possible to observe that also in these cases variations occur mainly between 0 and 10 cm in insulation thickness in accordance to *U*-value changes. After these values, the cooling energy needs remain almost constant. Higher insulation levels are correlated to low energy needs for both opaque and transparent closures. Nevertheless, such as was underlined in other works [10, 31], a different effect is expected between wall and roof insulation levels being the last positive (higher solar exposure in summer [32, p. 81]) and the first null or negative being less exposed to solar radiation and able in dissipating the internal stored heat by transmission losses. Nevertheless, for the purpose of this paper, wall and roof insulation thicknesses were changed together—see Fig. 25.3—and for this reason, it is not possible to isolate the effect on the cooling needs of vertical and horizontal insulation. A similar consideration can be done when different types of glass are considered, even if in these cases the insulation effect is also supported by low SHGC (solar heat gain coefficient) values for double and triple glazing systems. The SHGC of the triple glass is, in fact, almost the half of the one of the single one, resulting in a correlated reduction of the correspondent solar gains. For this reason, using a single glass the exchange with the environment will be higher and, without sufficient heat dissipation strategies of solar gain, cooling energy needs increase due to solar gains. On the other hand, triple glasses, even if they reduce the heat dissipation from inside to outside being insulated, ensure a higher solar gain protection. At general level, thermal insulation shows a positive effect on both heating and cooling consumptions (CNV off), although for the last some cases show a very limited opposite trends for very high insulation levels—e.g., in the domain 20–35 cm—such as can be underlined, for example, in the single glass and double glass lines of Fig. 25.6a.

By looking at energy need variations in relation to the building orientation, it is possible to state that lowest cooling needs values were simulated for the orientation of 90°, Fig. 25.6b, and for 270°, Fig. 25.6d. These are the two cases where the wall without windows is facing East and West orientations. Between these two scenarios, a slightly higher consumption was observed for the orientation in which the external long wall faces the West direction. This result is in line with expectations being the west-oriented façade a critical point for cooling purposes receiving solar radiation in the late afternoon when the environmental air is higher in temperature in respect to early morning. Regarding the other cases, the highest cooling energy needs are related to the building orientation in which windows faces both East and West and the external confining wall without window is south-oriented, Fig. 25.6c. Differently, the north oriented case, Fig. 25.6a, reports the lowest needs in the non-insulated configuration, but a lower absolute variation in between maximal and minimal insulation cases. Furthermore, in this case it is possible to see that the greatest variation in energy cooling needs is in the interval 0–5 cm of thickness of the insulating layer. This is because being one of the vertical walls less exposed to solar gains, the heat gain solar prevention due to insulation is less mitigating the losing in thermal dissipation potential from inside to outside spaces.

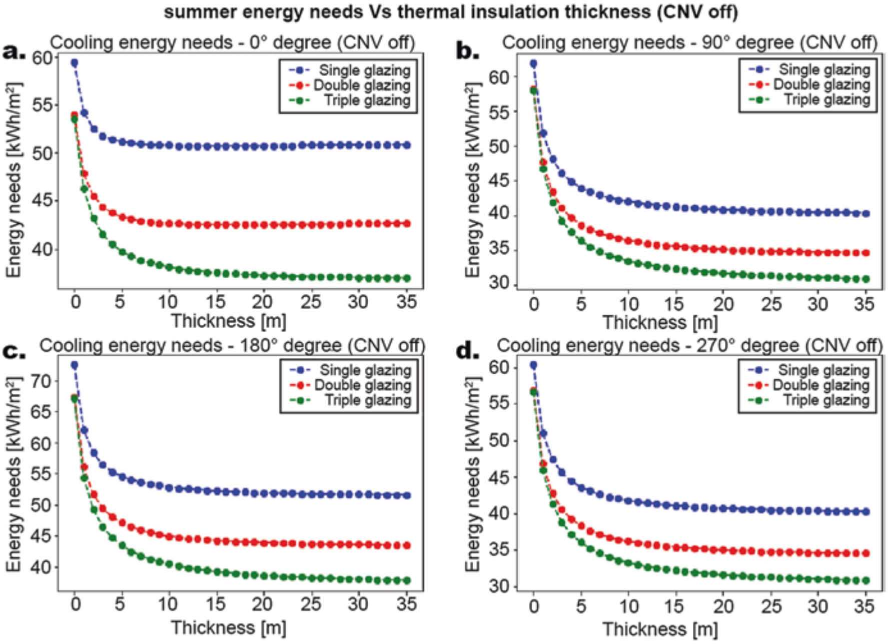

Fig. 25.6 Summer cooling energy needs with orientation of 0° from North direction (**a**), 90°(**b**), 180° (**c**) and 270° (**d**) and CNV off

Summer Energy Needs (CNV On)

In this section the effect of insulation on the cooling energy needs is defined when heat dissipation strategies are adopted. In particular, this analysis refers to the activation of ventilative cooling strategies—CNV—in order to exchange internal air with the external one when the last in lower in temperature and below the comfort threshold—see Table 25.1. Figure 25.7 is the counterpart of Fig. 25.6 when CNV is activated. It is possible to underline that also in this case similar trends are shown by the graphs. Cooling needs to decrease with insulation increase. Nevertheless, in these cases the counter-trends for high-insulated cases slightly visible in Fig. 25.6 are avoided being heat gains dissipated through ventilation. It is possible to note that CNV reduces the needs in all cases. Nevertheless, to study this reduction, Fig. 25.8 was elaborated showing the cooling energy need saving when CNV is activated in respect with configuration CNV off. This figure illustrates that even if for all insulation levels CNV allow to reduce the cooling needs, this reduction is proportional to the thickness of the insulation being more evident at lowest *U*-values. This result was expected, being heat dissipation a strategy to avoid the potential negative effect of heat gains capture of highly insulated spaces. Considering different glazing types, the same consideration is evident. Single glaze is the configuration that better exploits ventilative cooling potential because in this case solar gains and cooling needs are higher.

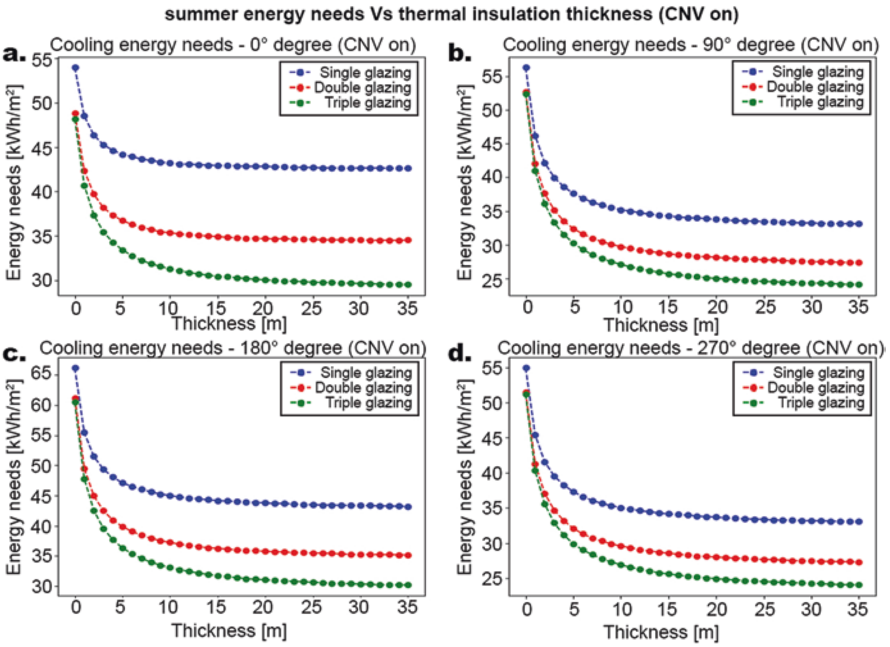

Fig. 25.7 Summer cooling energy needs with orientation of 0° from North direction (**a**), 90°(**b**), 180° (**c**) and 270° (**d**) and CNV on

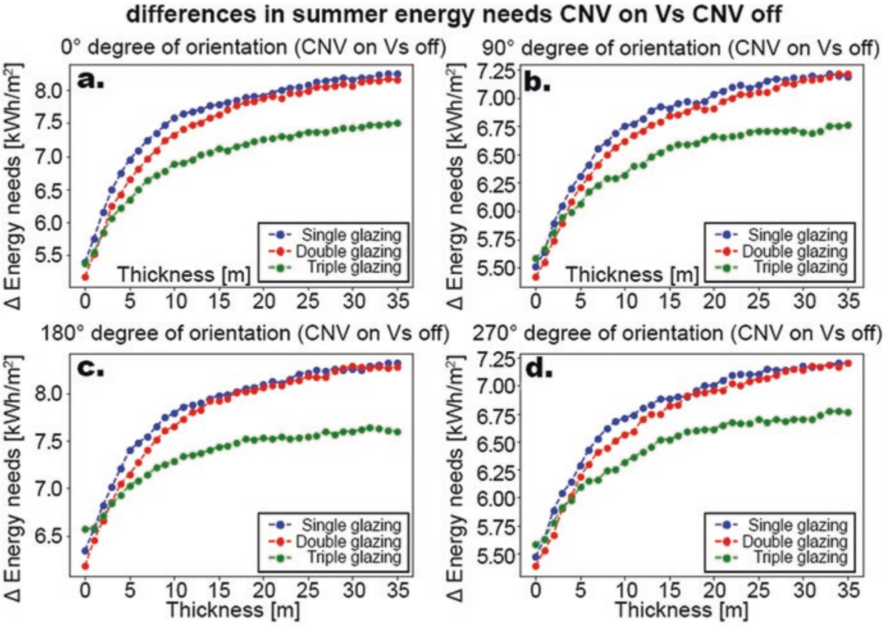

Fig. 25.8 Differences in cooling energy needs between CNV on and off cases for different thermal insulation thicknesses and building orientations

Discussion

1.1. In this section, economic aspects correlated to thermal insulation levels are discussed in section "Economic Analysis" and the application of regression models when random occupancy values are assumed are discussed in section "Regression Analysis". This last analysis allow to define potential correlation models between thermal insulation and energy needs being able to be used by designers since early-design phases for similar climate conditions. Furthermore, the inclusion of random occupancy variations helps in increasing the strength of the analyses in respect to potential perturbations of the starting set for boundary conditions.

Economic Analysis

The economic analysis was carried out in the following steps:

1. Evaluation of the initial cost of the insulation panels in relation to the various thicknesses used in the energy analysis
2. Estimation of the annual energy saving for space heating and cooling for the various insulation panel thicknesses
3. Comparison between the above two estimates in order to define the optimal thickness whereby the initial cost equals the annual energy saving
4. Calculation of the discounted payback period (DPP) for the various insulation thicknesses

Energy Saving vs. Initial Cost of Insulation Panels

The initial cost, $C_{ins_{th}}$, of an insulation panel with a specific thickness and area of 1 m^2, is given by Eq. (25.2):

$$C_{\mathrm{ins}_{\mathrm{th}}} = \left(I_{\mathrm{ins}_{\mathrm{mat}}} + L_{\mathrm{ins}}\right) \times \mathrm{th}_{\mathrm{ins}} \times A[€] \tag{25.2}$$

where:

$I_{ins_{\mathrm{mat}}}$ = initial cost, per unit of thickness and area, of an insulation panel composed of the considered material (XPS), including VAT [€/m^2];

$\mathrm{th}_{\mathrm{ins}}$ = thickness of the insulation panel [m];

A = area of the insulation panel [m^2];

L = labor cost, lumped estimated based on an interview with construction workers (35% of the selling cost).

For the present analysis, $I_{ins_{\mathrm{mat}}}$ = 0.70 €/$\mathrm{cm}_{\mathrm{th}}$,$\mathrm{m}^2$ and the total unitary cost, including labor, is 0.95 €/$\mathrm{cm}_{\mathrm{th}}$,$\mathrm{m}^2$.

The annual energy cost for space heating and cooling, $C_{ins_{th}}$, related to each insulation panel thickness, was calculated using the following Eq. (25.3):

$$C_{\mathrm{en}_{\mathrm{th}}} = \left(E_{\mathrm{heat}_{\mathrm{th}}} + E_{\mathrm{cool}_{\mathrm{th}}}\right) \times C_{\mathrm{un}_{\mathrm{el}}} \, [€] \tag{25.3}$$

where:

$E_{\mathrm{heat}_{th}}$ = annual energy need for space heating of the considered building unit, related to the use of a specific insulation panel thickness [kWh];
$E_{\mathrm{cool}_{th}}$ = annual energy need for space cooling of the considered building unit, related to the use of a specific insulation panel thickness [kWh];
$C_{un_{el}}$ = unitary cost of the delivered energy, depending of the source, here considered as electricity for both heating and cooling [0.20 €/kWh].

The intersection between the two curves, occurring at a thickness of about 6 cm, represents the value of the insulation thickness for which there is a one-year return on investment (simple pay back period)—see Fig. 25.9.

Discounted Payback Period

The discounted payback period (DPP) of the investment related to the application of insulation panels, i.e., the period of time required for the accumulated net savings due to the annual energy need reduction, to equal the initial cost of the insulation panels, with all figures expressed in present values, can be calculated using the following Eq. (25.4), while results are shown in Fig. 25.10.

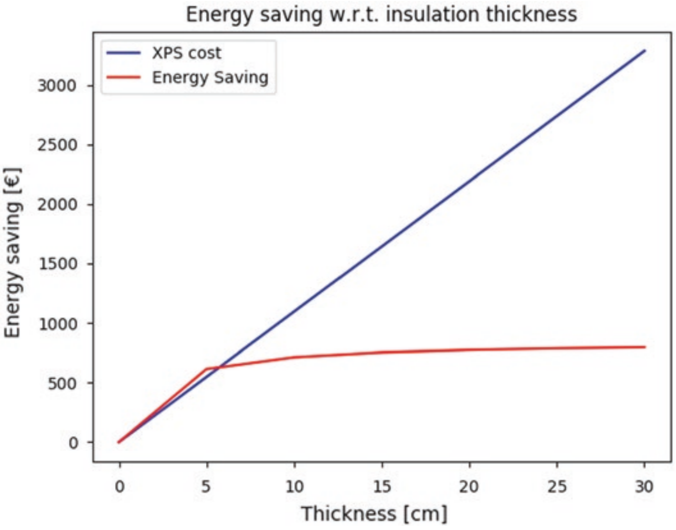

Fig. 25.9 Energy cost saving (red line) and initial cost of insulation panel (blue line) as a function of insulation panel thickness

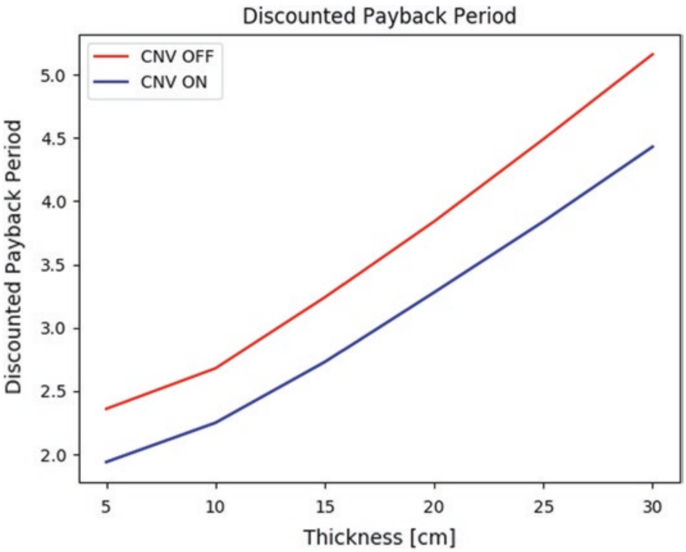

Fig. 25.10 DPP (years) of the initial investment related to the application of insulation panels of various thickness, for both configurations, with and without CNV

$$DPP = \frac{\ln\left(\dfrac{1}{1-\left(\dfrac{IIC \times i}{NAS}\right)}\right)}{\ln\left(1+i\right)} \tag{25.4}$$

where:

IIC = initial investment cost; *NAS* = net annual saving; *i* = interest (discount) rate expressed as a decimal considered = 0.01.

Regression Analysis

Using the reference building and the base ∗.idf files, a random variable has been added to the original scenario in order to obtain a train and a test dataset and evaluate, based on a regression technique, the polynomial degree of the function that better approximate the energy need behavior of the previous scenarios. Ten variations were considered for all simulated case in the base analysis for 12,960 *EnergyPlus* simulations. Considering the dimension of the dataset, the subdivision of results in between train and test was of 50% each in order to prevent overfitting risks on the training database. As mentioned in section “Methodology”, the randomness has been introduced by varying the average number of people in the building; the distribution of this parameter has been chosen as a random Gaussian distribution with a mean value of two people and a variance such that occupancy values are in the domain {0–4} persons. Starting from the original ∗.idf files, thanks to the Python library Eppy, the occupancy value has been changed and, for each new value, the EnergyPlus simulation has been run. It is worth to notice that this assumption for the data randomization is consistent: the presence of people in a building influence the consumption in both scenarios being the human body a source of heat. For the winter case, it has been verified that the energy consumption decreases by crowding up the building while, in summer simulations, more people are in the cooled space and more will be the cooling needs. Finally, in order to be able to compare all different considered scenarios (orientation and windows), the same random-generated occupancy matrix was used to generate all the simulations for the train database, while another matrix was used for simulating all the test samples.

Considering heating energy needs, Fig. 25.11 plots the results for the single glass window considering all orientations. As was expected, being the behavior of the four-orientation scenarios really close to each other, the best polynomial degree is the same for all cases—see Table 25.3. Nevertheless, these four scenarios differ in

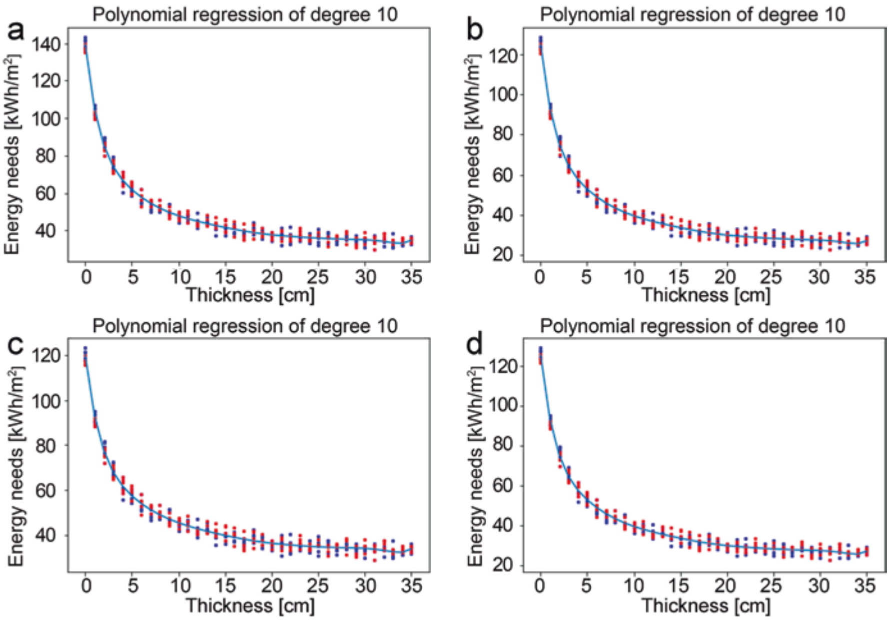

Fig. 25.11 Regression for winter scenarios with single glazing window

Table 25.3 Heating case, single glazing—best polynomial degree and related RMSE

Orientation	RMSE	Polynomial degree
0°	2.41	10
90°	2.23	10
180°	2.36	10
270°	2.23	10

Table 25.4 RMSE for each calculated degrees of polynomial regression curves (the reported sample case refers to the single glazing window, 0° in orientation)

Polynomial degrees	RMSE Test dataset	RMSE Train dataset	Polynomial degrees	RMSE Test dataset	RMSE Train dataset
1	14.12	14.71	8	2.49	2.49
2	9.07	9.62	9	2.43	2.48
3	6.25	6.53	*10*	*2.41*	*2.46*
4	4.55	4.65	11	2.44	2.44
5	3.48	3.50	12	2.47	2.41
6	2.87	2.81	13	2.47	2.41
7	2.63	2.62	14	2.47	2.41

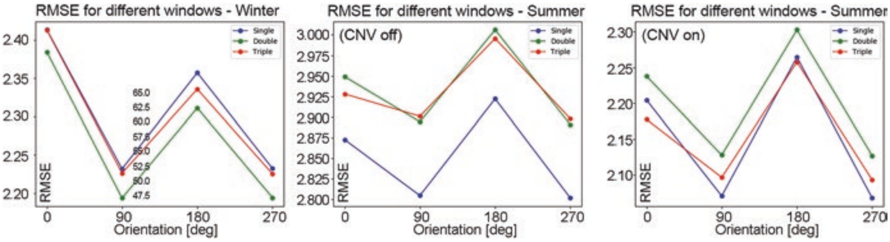

Fig. 25.12 (**a**) RMSE of best polynomial degree curves in the winter simulation database; (**b**) same analysis for summer cases with CNV mode off; (**c**) summer cases with CNV mode on

the RMSE due to differences in the weight of occupancy internal gain component in respect to the solar one—which is the one that varies with orientation. The best polynomial degrees (scenarios) have been selected considering their RMSE values by looking at the smallest one before that RMSE values start to increase again. This behavior is called overfitting and happen when the model starts working very well with the train dataset, but its performances decrease when it is compared with a test dataset. Table 25.4 clearly shows this behavior for the winter heating energy needs in the single glass window and a 0° of orientation. As can be seen, after the tenth degree, the model better fits with data of the train dataset while the RMSE between the obtained values and the test dataset start to increase again.

The best regression model of each case was also plotted in Fig. 25.11.

The same approach described for the single glazing case was applied to all considered window and orientation configurations in both seasons. Figure 25.12a shows how the RMSE value for the best polynomial degree changes for all window types and orientations considering the winter heating energy need.

Differently, for cooling needs it is possible to see simulation results for the single glazing windows in Fig. 25.13 for the case without CNV. In this scenario, the best polynomial degree results to be the eight for all orientations, while the RMSE ranges around 2.8–2.9 for this degree being higher than the one reached during the heating need analysis. The same statement is even more evident for double and triple glazing systems—see Fig. 25.12b. This is due to the fact that summer energy

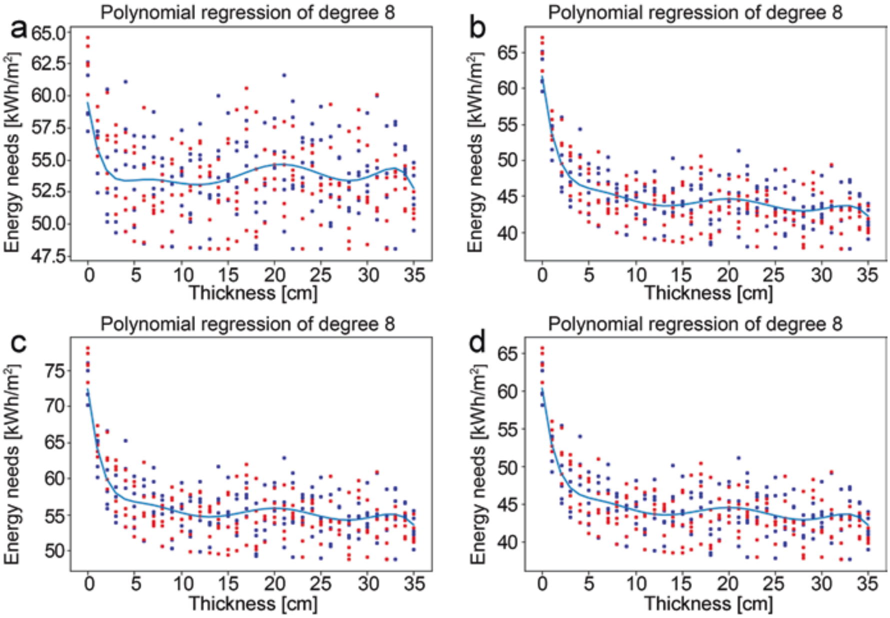

Fig. 25.13 Regression for summer scenarios (CNV off) with single glazing window

needs are highly influenced by internal gains in comparison to the heating season because the discrepancies between comfort threshold and environmental air temperatures in winter are higher than the opposite ones in summer. Nevertheless, the analysis and the regression model under the perturbation effect of random internal gains confirm the general trends underlined for the base case, even if with higher occupancies the effect of insulation may be less positive. Especially for case with orientation 0°, it is evident that when solar gains are limited (the long exposed façade is north facing), variations in the internal ones may sensibly affect the potential of high levels of insulation.

Furthermore, when CNV mode is on, the same analysis performed on single glazing systems shows a polynomial behavior similar to the base case—see Fig. 25.14. As was expected, and in line with literature considerations, when CNV is activated, variations in internal gains—e.g., random presence of people—is impacting less the results due to the fact that ventilative cooling acts as a natural dissipative technique. In these cases, in fact, the RMSEs for all orientations are considerably lower than the previous summer database such as it is underlined in Fig. 25.12c. For this reason it is possible to state that CNV is a good opportunity not only to reduce the cooling energy needs, but also to potentially absorb discrepancies between expected and obtained needs when people occupancy levels change, such as may arrive in real building operation. Figure 25.15 compares two of the obtained graphs for these two CNV modes—off in Fig. 25.15a and on in (b)—including all calculated polynomial curves, from degree 1 to 15. These graphs confirm what was mentioned before.

Figure 25.16 Summary of final results including best chosen polynomial curves

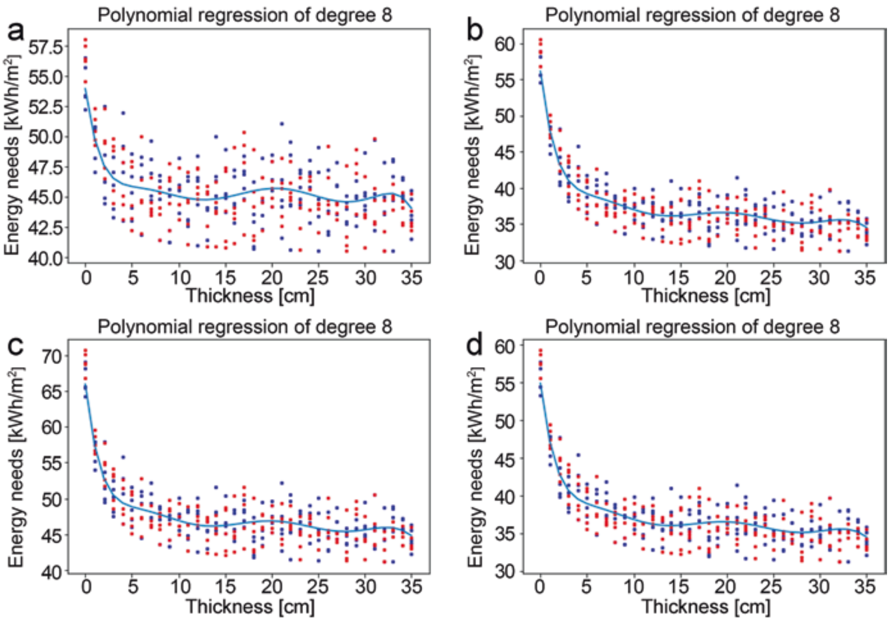

Fig. 25.14 Regression for summer scenarios (CNV on) with single glazing window

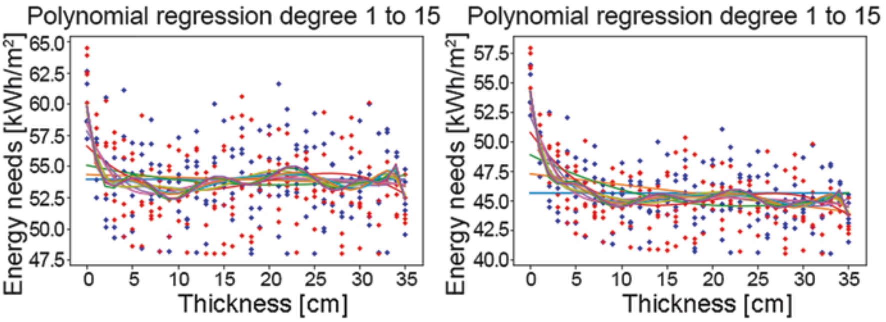

Fig. 25.15 Comparison between summer scenarios for single glazing window orientation 0° including all calculated polynomial curves and considering (**a**) CNV off, and (**b**) CNV on

Conclusions

The paper represents one of the first applications of an innovative performance-driven approach to environmental and technological building design, expanding the methodology of the need-performance design method, proper of the Italian architectural technology field, thanks to the exploit of actual potential of current calculation tools and machine related to IT (information technologies) instruments. The proposed approach is based on the usage of massive amount of simulations

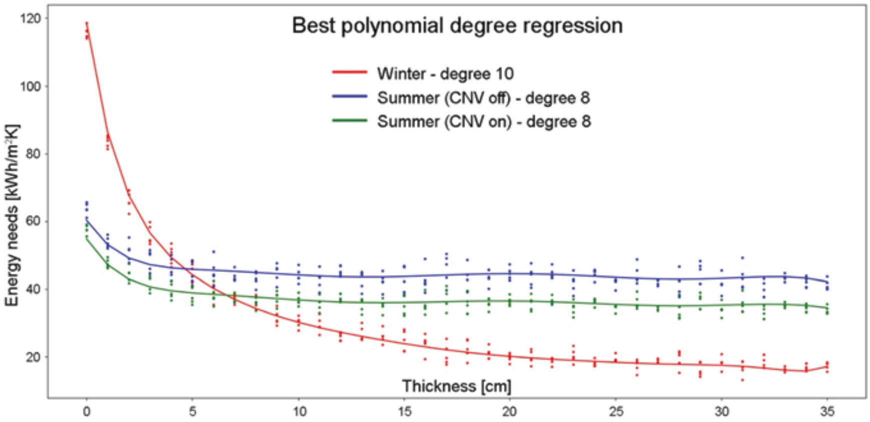

Fig. 25.16 Summary of final obtained results including the best calculated polynomial curve for heating, cooling (CNV off), and cooling (CNV on)

driven by Python coding and evaluated for tend model definition using statistical polynomial regressions and noise variable management.

A sample application based on a reference residential unit of about 70 m^2 was simulated using EnergyPlus to optimize thermal insulation levels considering both cooling and heating energy needs, together with the potential effect of CNV activation and different orientations. The effect that random variations on specific simulation variables, differing from the target and main input ones, was analyzed to test statistical significance of results and correlated suggestion for early-design choices in order to test their resistant to perturbation phenomena that may arrive in real building operation. By results it was underlined that thermal insulation has a positive impact on both cooling and heating energy needs for the case studied located in Turin, when both wall and roof insulation thickness are changed equally. Furthermore, it was confirmed the importance of ventilative cooling solutions to (1) reduce the cooling energy needs, and (2) reduce the risk of overheating and overcooling consumptions under random occupancy variations.

Results only explore a first part of the potential of the proposed methodological approach and suggest that further investigations on this topic may bring innovative models suggesting to designers the best optimization strategies for technological choices. This approach shows also that it is nowadays possible to fully expand the methodology of the performance-driven design based on the programming of the users → activities → needs → requirements ← performance design flow. Further researches on this field are hence under development by authors.

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