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Extensive Utilization Of Dynamic Simulation For Sensitivity Analysis And Optimization Design Of Refurbishment Measures

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ABSTRACT

Statistics and, in particular, sensitivity analysis represent an important tool for the building designer to find information about which parameters have the largest potential in reducing the energy consumption or which are the most crucial to focus on in the different phases of the project process. The application of dynamic simulation to a large number of configurations (i.e. the extensive simulation) to find the optimal solution either considering only the energy aspects or also the economic impacts and not only to evaluate a small set of possible alternatives, represents in that perspective a new approach to the building design, in particular for refurbishment considerations.

This work aims to evaluate and generalize this kind of approach with its application to the refurbishment of residential buildings.

The considered design solutions represent the most common measures of improvement of the performance of opaque and transparent envelope, such as the insulation level of walls and windows and the solar properties of the glazings. Different starting cases characterized by different envelope thermal inertia, corresponding to three massive materials (timber, clay and concrete), and different geometrical features were studied.

A large number of environmental conditions, envelope characteristics and refurbishment interventions have been analyzed within a factorial simulation plan. Among those parameters, the ratios between the dispersing envelope and the volume conditioned (considering 3 different floors of a building – the top, the intermediate and the ground floor), the windows size (small or large size) and their distribution (South, East or West oriented), the level of insulation of the opaque envelope (starting cases without insulation, poor insulated and high insulated cases) and the kind of glazings (starting cases with single glasses and improved cases with double or triple glasses with high or low Solar Heat Gain Coefficient, SHGC) have been examined. Three Italian climates (Milan in the North, Rome in the center region and Messina in the South) were considered as representative of the Southern Europe.

The inferential statistical analysis has been used to identify the predominant factors in each refurbishment solution and the economical savings both in heating and in cooling.

1. INTRODUCTION

Compared with the industrial and transportation sectors, buildings are responsible of approximately the 40% of the total energy demand. The International Energy Agency underlines how the residential sector is the major responsible in energy consumption and it has recently approved the Annex 56 activity with the purpose of analysing the potentiality of building renovation in energy saving. In Italy two-third of the building stocks were built before the adoption of the first energy legislations (Law no. 373 of 1976), with energy performance dramatically lower than the present laws prescriptions. For this reason energy retrofit actions present an enormous potential in energy saving and they will represent more and more the predominant subject of construction projects.

The main issue with the energy refurbishment of building is that, in most of the cases, the decision maker, either a public manager or a private owner, is not prepared to evaluate and compare the solutions. In refurbishment, different retrofit measures lead to multiple action combinations that should be considered. Just to consider the measures on the envelope, the improvement of thermal transmittance of opaque envelope by means insulation materials, the introduction of windows with higher thermal insulation and/or the choice of different solar control glazing are the most common. It is also possible to introduce efficient energy supply technologies and RES-based solutions.

The definition of the optimal combination of measures either for energy saving or for economical reasons is not easy. To make the right choice, it is important to evaluate correctly the initial performance and energy costs and to give a right estimation of the investment costs and of the operational savings potential for each retrofit combination.

The improvement of the envelope of the building could reduce significantly its global energy consumption. Reducing the thermal losses through the envelope during the heating season and the solar gains through the windows during the cooling season leads to considerably lower energy demand. A lot of studies carried out analysis on the optimal thickness of insulation and on different types of glazing, comparing the investment cost to the reduction of energy costs. Kaynakli (2008, 2012) investigated the variation of the optimum insulation thickness for various design properties (glazing type and area) and for different types of fuels. Bolattürk (2008) underlined the variation of optimum insulation thickness and payback period for seven cities situated in different climatic regions. Özkan and Onan (2011) focused their attention on the variation of insulation thickness altering the glazing area percentage (range from 50% to 10%). Lollini *et al.* (2006) evaluated the benefits of good insulated building envelopes and the proper thickness of insulation for eight different cities that represent the main Italian climates. All those authors demonstrate that it is required an evaluation of a large number of parameter combinations, to define the optimum value of thickness insulation.

The recourse to dynamic simulation codes allows the detailed analysis of the possible alternatives. An extensive simulation use is then required to study the behavior of the optimal solution for different building configuration and initial situation and a huge amount of data have to be analyzed. In order to define quickly the most important building parameters and the relevance of different factors, some authors (Heiselberg, 2009) suggest to use statistics, in particular the sensitivity analysis. Jaffal *et al.*(2009) and Ylidz and Arsan (2011) proved that the use of statistical models reduces the number of combination to investigate and combines the speed of simplified models with the precision of dynamic simulation. Using regression techniques, by doing a limited number of simulation, is possible to generate a function that relates the energy demand to environmental and design variables and to find out the optimum solution from the different configurations of retrofits actions.

This work considers an uninsulated single-storey model of residential flat with variable characteristics (different windows size and orientation, envelope materials, ratios between the dispersing envelope and the conditioned volume) sited in three climatic conditions (Milan, Rome and Messina).

Different retrofitting interventions, both on the opaque and on the transparent envelope, are evaluated considering the monthly energy needs and the total cost of the investment. Finally, the results have been elaborated to identify the predominant factors in each retrofitting context by means of the inferential statistical analysis.

2. REFERENCE CASES AND SIMULATION HYPOTHESES

The reference starting case is a base module of 100 m^2 of square floor and 3 m of internal height located in three different Italian cities: Milan ($HDD_{20} = 2404$), Rome ($HDD_{20} = 1415$) and Messina ($HDD_{20} = 707$), which represent the variability of the Italian climatic areas (Northern, Central and Southern regions).

The building has been modelled as a single thermal zone, like an apartment of a building. In particular, three different positions in the multi-storey building have been considered:

- the top floor of the building (*TF*), with a dark coloured roof (α=0.6) directly exposed to the external environment and a floor adjacent to another conditioned zone considered as adiabatic (S/V= 0.73);
- the intermediate floor (*IF*), with both the ceiling and the floor adjacent to another conditioned zone and assumed as adiabatic (S/V = 0.40);
- the ground floor (*GF*), with the ceiling adjacent to another conditioned zone (and assumed as adiabatic) and the floor exposed to the external environment without solar gains and sky vault infrared losses (S/V= 0.73).

Table 1: Characteristics of the reference starting cases

Characteristics of opaque envelope							
		Thickness (m)	Thermal Conductivity (W m^{-1} K^{-1})	Thermal Resistance (m^{2} K W^{-1})	Thermal Capacity (kJ m^{-2} K^{-1})	Density (kg m^{-3})	Specific Heat capacity (J kg^{-1} K^{-1})
Materials	Timber	0.10	0.13	0.77	75	399	1880
	Clay	0.20	0.25	0.80	150	893	840
	Concrete	0.30	0.37	0.81	300	1190	840
Characteristics of windows							
Glazing				Single-pane glass U_{gl} = 5.693 W m^{-2} K^{-1}			
Frame				Metal without thermal break U_{f} = 3.2 W m^{-2} K^{-1}			
Percentage ratio A_{gl}/A_{fl}				Size 1: 11.67%			
				Size 2: 23.34%			
Orientation of the windows				East			
				South			
				West			

The vertical walls are all external and oriented towards the cardinal orientation. The opaque envelope is a simplified structure composed of a single massive layer with a thermal resistance equal to about 0.8 m^{2} K W^{-1}. In order to consider different thermal capacities, three materials - timber, clay block and concrete - have been analysed. The thermo-physical characteristics of the materials have been reported in Table 1.

The windows of the reference cases are composed by a single-pane glass (U_{gl} = 5.693 W m^{-2} K^{-1}, SHGC = 0.810) and a metal frame without thermal break (U_{f} = 3.2 Wm^{-2} K^{-1}). The frame area is the 19.9% of the whole window area. Two glazings sizes have been analysed, expressed as ratios of window area on floor area, and three possible orientations have been considered as reported in Table 1. For each case, all the windows have the same orientation.

The ventilation rate is 0.3 ach/h the internal gains are 373.7 W, a half radiative and a half convective, in accordance with the Italian technical standard UNI/TS 11300-1:2008.

The effect of the thermal bridges has been neglected. In fact, the weight of thermal bridges can be approximated as an increase of the whole thermal losses by a fixed percentage, which, in accordance with the technical standard UNI/TS 11300-1:2008, is the same (5%) both for the non-insulated envelopes and for the insulated ones with minimized thermal bridges.

Combining the climates, the geometric characteristics, the boundary conditions of the thermal zones, the three different opaque structures and the orientation of the windows, 162 different reference cases have been defined.

The energy need has been calculated by means of the simulation code EnergyPlus 7 (U.S. DoE, 2011). The considered glazings have been modelled with Window 6.3 (Lawrence Berkeley National Laboratory, 2011). The simulation hypotheses are the following:

- fixed values for convection coefficients have been calculated from the standard EN ISO 6946:2007; the radiative coefficients are derived by EnergyPlus from the surfaces emissivity (0.9) and temperatures;
- the solar distribution algorithm *FullExterior* has been followed –the diffuse solar radiation is uniformly distributed on the internal surfaces and the beam solar radiation entering through the windows falls on the floor and the amount reflected is then added to the diffuse component;
- for the long wave radiation internal exchanges, a detailed view factor model and grey surfaces are considered by EnergyPlus;
- the EPW weather files have been modified in order to get the hourly climatic data in accordance with the Italian Standard UNI 10349:1994 for Milan, Rome and Messina using the TRNSYS subroutine Type 54 Weather Data Generator (Solar Energy Laboratory, 2005);
- the heating and the cooling setpoint have been fixed to 20 °C and 26°C in accordance with the UNI/TS 11300-1 prescriptions for residential buildings, but they are applied all year long thus no heating and cooling seasons have been defined.

3. RETROFITTING DESIGN PARAMETERS

The analysed refurbishment interventions for improving the thermal performance of the envelope are (Table 2):

- the application of an insulating polystyrene layer with two possible thicknesses (0.05 m and 0.10 m) installed on the external surface of the original envelope;
- the substitution of the window frame with a thermal break wood/aluminium one (U_f = 1.2 Wm^{-2} K^{-1});
- the use of different glazing types, two double and two triple, with argon/krypton filling and a low-e treatment, with two different solar heat gain coefficient.

In Table 3 the dynamic characteristics of the reference vertical walls and the refurbished ones calculated in accordance with the standard EN ISO 13786:2007 have been indicated. The interventions on the opaque envelope, on the transparent components and on both, have been simulated for all the 162 reference cases.

Table 2: Retrofitting interventions

<table>
<tr><td colspan="6"><i>Opaque envelope</i></td></tr>
<tr><td></td><td>d
(m)</td><td>λ
(W m^{-1} K^{-1})</td><td>c
(J kg^{-1} K^{-1})</td><td colspan="2">ρ
(kg m^{-3})</td></tr>
<tr><td rowspan="2">Insulation layer</td><td>0.05</td><td rowspan="2">0.04</td><td rowspan="2">1470</td><td colspan="2" rowspan="2">40</td></tr>
<tr><td>0.10</td></tr>
<tr><td colspan="6"><i>Transparent envelope</i></td></tr>
<tr><td></td><td colspan="3"></td><td>U_{gl}
(W m^{-2} K^{-1})</td><td>SHGC
(-)</td></tr>
<tr><td rowspan="4">Glazing</td><td colspan="3">DH – Double Glazings with high SHGC
(4/9/4 filled with krypton, low-e treatment on both glasses)</td><td>1.140</td><td>0.608</td></tr>
<tr><td colspan="3">DL – Double Glazings with low SHGC
(6/16/6 filled with krypton, low-e treatment on both glasses)</td><td>1.099</td><td>0.352</td></tr>
<tr><td colspan="3">TH – Triple Glazings with high SHGC
(6/12/6/12/6 filled with krypton, low-e treatment on all the glasses)</td><td>0.613</td><td>0.575</td></tr>
<tr><td colspan="3">TL – Triple Glazings with low SHGC
(6/14/4/14/6 filled with argon, low-e treatment on all the glasses)</td><td>0.602</td><td>0.343</td></tr>
<tr><td>Frame</td><td colspan="5">Wood/aluminium with thermal break U_f= 1.2 W m^{-2} K^{-1}</td></tr>
</table>

Table 3: Thermal characteristics of the refurbished opaque envelope (a vertical wall has been considered)

Material for the internal layer	U_w (W m^{-2} K^{-1})			Y_{ie} (W m^{-2} K^{-1})			Δt_{ie} (h)		
	0.00 m	0.05 m	0.10 m	0.00 m	0.05 m	0.10 m	0.00 m	0.05 m	0.10 m
Timber	1.061	0.456	0.290	0.885	0.240	0.129	-3.52	-5.62	-6.76
Clay Block	1.027	0.456	0.288	0.593	0.127	0.063	-6.29	-8.69	-9.48
Concrete	1.016	0.448	0.287	0.292	0.045	0.024	-10.08	-12.40	-13.12

4. RESULTS AND DISCUSSION

The 2430 yearly heating and cooling energy needs simulated by EnergyPlus have been used as input for the economic analysis, considering the costs elements and the parameters reported in Table 4. The cost functions for the insulation of the opaque elements have been determined using the data of the Regional Price List of Lazio. The real interest rate has been calculated from the Italian inflation rate (3.3%) and the Italian 20 year long Btp (in the range 5.5% - 6%) using the data by the Ministry of Economy updated on February 2012. Both for the heating and the cooling systems efficiency different scenarios have been studied: the base scenario (100% of the base performance), the scenario with a high performance (120% of the base value) and the scenario with a poor performance (80% of the base value); combining the possibilities 9 different scenarios for the conditioning systems were obtained. No subsidisation form has been considered in the analysis for the refurbishment measurements.

The energy and economic results are reported in Figures 1 and 2. As regards energy, the deviations between the heating and cooling energy needs for the retrofitted cases and the ones for the reference cases have been considered. As regards the economic aspects, the differential Net Present Value (*NPV*) distributions, i.e. the actualized difference between the total costs (that means the investments costs plus the running costs) related to the cases with retrofits, and the running costs of the corresponding reference cases have been represented.

Table 4: Costs and base parameters for the economic analysis

Investment variables		
Investment for the insulation of 1 m^2 of vertical wall	$IC_{VW} = (1.60\ x + 38.53)$ € m^{-2}, where x is the insulation thickness	
Investment for the insulation of 1 m^2 of horizontal wall	$IC_{HW} = (1.88\ x + 8.19)$ € m^{-2}, where x is the insulation thickness	
Investment for 1 m^2 of window	DH	IC_{DH} = 511.81 € m^{-2}
	DL	IC_{DL} = 555.77 € m^{-2}
	TH	IC_{TH} = 604.62 € m^{-2}
	TL	IC_{TL} = 575.31 € m^{-2}
Fuel Cost(1)	85 c€ Sm^{-3}	
Lower Heating Value of the Fuel(2)	32.724 MJ Sm^{-3}	
Electricity Cost(1)	6.94 c€ MJ_{el}^{-1}	
Length of the investment	20 years	
Real interest rate	2.5%	
Heating and Cooling Systems		
Overall base heating efficiency, η_h	80%	
Overall base cooling *COP*, η_c	3	
(1) Autorità per l´Energia Elettrica e il Gas, 2011, *Relazione annuale sullo stato dei servizi e sull'attività svolta,* Milan, Italy. (2) Ministry of Economic Development, 2011, *Bilancio Energetico Nazionale 2010,* Rome, Italy		

Considering all the costs as positive, a negative value of the differential *NPV* means that the intervention is economically advantageous, with the discounted savings overbalancing the initial investment.

The results have been distinguished with respect to the different type of envelope materials, of glazings and to the various thicknesses of insulation, distinguishing the three considered locations, the three floor positions. Only the energy deviations and the *NPVs* for the cities of Milan and Messina for and the cases with smaller windows are shown in the boxplots of Figures 1 and 2. The results for Rome lay between those of Milan and Messina. The diagrams represent the maximum, the minimum, the first, the interquartile range (*IQR*) and the median of all the cases compared.

The results for the three different cities show that the effectiveness of the different retrofit interventions in energy savings are more relevant in Milan for the heating needs and in Messina for the cooling needs, as one could expect. In Milan the *NPVs* prove the economic convenience for a large number of refurbishment measurements but in Messina and Rome the investment appears often disadvantageous.

The three different floor positions of the apartment, *TF*, *IF* and *GF*, strongly influence the energy effectiveness of the measures: considering the medians, in the *IF* the retrofits actions have minor effects on the heating needs than in the top and the ground floors while on the cooling needs the effects are between those of the two other floors.

As regards the economic impact of the refurbishment measures over the three position summarized in *NVP* boxplots, the median values of the top floor presents the greater economical convenience even if this is more evident in Milan than in Messina. The efficacy of refurbishment measures seems very influenced by the geometrical ratio S/V especially for colder climate.

About the grouping criteria, analyzing the different kinds of envelope material (Figures 1a and 2a), the chosen refurbishment measures produce more benefits for the timber structures than for the clay block and the concrete ones, both for heating and cooling energy savings.

The effect of the different kinds of window is strongly related to the SHGC (Figures 1b and 2b), in particular for the cooling needs, for which a low SHGC value grants larger savings. In the heating context, even if a high value is preferable, the SHGC impact is more limited. Especially for the climates where the cooling needs are prevalent, the energy improvement due to the windows substitution often does not involve an economic advantage: in fact the high investment costs for windows with enhanced thermal properties is not easily balanced by the running savings.

In all the localities the increase of the insulation´s thickness reduces the energy demands for the heating, especially in Milan with its colder climate (Figures 1c and 2c). For the cooling, the insulation generally reduces the thermal losses towards the external environment increasing the energy needs of the building. However in those cases and periods where the external temperature is persistently larger than the internal one the insulation can provide some benefits. Under an economic point of view, in Milan the increase of the insulation thickness is economically advantageous while in Messina not at all.

Although the boxplots in the figures refer only to the cases with the smaller extension of windows (11.67 % of floor area), with larger glazing areas the trends are similar. The only difference is a larger dispersion, i.e. a larger *IQR*, of the data for the cooling needs deviations. A larger *IQR* means that the independent variables considered in the grouping criterion are less effective in conditioning the energy deviations or that the net present values and their variation is influenced by other factors. As regards the *NPVs*, the *IQRs* are also generally wider for the larger window size configurations in Messina, while in Milan, for the intermediate floor cases some tighter ranges are registered when grouping by glazings type. From the data it is also possible to point out that the retrofit actions on energy heating reduction tend to become in general more efficient for the larger windows, even if the effect is less relevant in Messina than in Milan. Similar considerations could be done for the cooling deviations but in this case the differences in results are more consistent for Messina respect of Milan. This is probably due to the fact that larger windows emphasize the improvement of the glazing thermal transmittance (which becomes more significant than the one of the opaque envelope) when considering heating, and the improvement in SHGC for the cooling needs. From economic point of view the larger are the windows, the higher is the *NPV* for all the localities and in all cases when windows are substituted.

Changes and in particular improvements of the energy efficiency of the system, do not alter the above considerations.

5. STATISTICAL ANALYSIS

A statistical analysis of the yearly *NPV*s has been performed. This time the *NPV* of the investment (following denoted with NPV_{IC}) has been re-calculated, considering not the economical savings but the total investment costs of each alternative (investment plus running costs), in order to have only positive values. The inferential statistical technique employed is a multivariate linear regression with a confidence level of 95%. In the model developed, the added variables have been selected through the stepwise algorithm among:

a. the variables related to the opaque envelope:
  - the area weighed mean thermal transmittance of the opaque components U_{env} [W m^{-2} K^{-1}];
  - the area weighed mean periodic thermal transmittance $Y_{ie,env}$ [W m^{-2} K^{-1}] and time shift $\Delta t_{ie,env}$ [h] of the opaque elements;
  - the product of the total opaque envelope multiplied by its internal heat capacity, determined in accordance with the EN ISO 13786:2007 detailed approach, $\Delta\kappa_i \cdot A_{tot}$ [kJ K^{-1}];
  - the area of the surfaces exposed to the external environment A_{env} [m^2];

b. the variable related to the windows:
  - the area of the whole windows A_{win} [m^2];

c. the variables describing the external solicitation of the opaque envelope:
  - the heating degree days HDD_{env} and the cooling degree days for the opaque envelope $CDD_{env,}$, determined in accordance with the Equations (1) and (2) with a sol-air temperature defined as in Equation (3) [K d];

d. the variables describing the external solicitation of the transparent envelope:
  - the heating degree days HDD_{gl} and the cooling degree days for the glazings CDD_{gl}, determined in accordance with Gasparella *et al.* (2011), where the sol-air temperature for glazings is defined by Equation (4) [K d];

e. the variables related to the overall heating and cooling systems efficiency η_H [-] and η_C [-].

The heating/cooling degree days for the opaque envelope have been elaborated starting from the hourly profile of solar radiation on each wall, external air temperature and sky temperature on a year period. For each external wall the values of the yearly *HDD* and *CDD* have been calculated and then the area weighed mean *HDD* and *CDD* have been elaborated.

$$HDD_{env} = \sum_{i=1}^{365}(20-\theta_{sol-air,env}) \tag{1}$$

$$CDD_{env} = \sum_{i=1}^{365}(\theta_{sol-air,env}-26) \tag{2}$$

where:

$$\theta_{sol-air,env} = \theta_e + \frac{I\alpha + h_{r,sky}(\theta_{sky}-\theta_e)}{h_{se}} \tag{3}$$

and 20 °C and 26 °C are, respectively, the heating and the cooling temperature of setpoint.

For the calculations of the equivalent cooling/heating degree days of the transparent surfaces, the equations used are similar to Equations (1) and(2), despite of the sol-air temperature, which is expressed by:

$$\theta_{sol\text{-}air,gl} = \theta_e + \frac{gI}{U_{gl}} + \frac{h_{r,sky}(\theta_{sky} - \theta_e)}{h_{se}} \tag{4}$$

Glazing characteristics (SHGC and U_{gl}) have not been considered as independent main factor because already present in the definition of the sol-air temperature for the glazings.

The model developed has been described in Table 5. The standardized coefficients are defined as the product of the non-standardized coefficients and the ratio between the standard deviations of the independent variable considered and that of the dependent one. The larger the standardized coefficient, the larger is the relative impact of both the variability and the correlation of the independent variable on the dependent one. The main influencing parameters for the NPV_{IC} are the windows area, the opaque envelope area, and the HDD_{env} for the opaque envelope and the CDD_{gl} for the glazings. The cooling degree days for the opaque envelope have a slightly negative coefficient: it could be correlated to the advantages realized by means of the insulation in reducing the solar gains by transmission which can be much more useful for warmer climate. The higher are the performances of the systems, the lower are the NPV_{IC}. A larger thermal capacity (e.g., a concrete structure) corresponds a lower NPV_{IC}; it should be noticed that insulating the opaque envelope externally the thermal capacity has little changes: it is slightly reduced for the concrete and the clay block and it is increased for the timber structure. The periodic thermal transmittance has a positive correlation with the dependent variable.

Table 5: Regressive model elaborated for the NPV_{IC} [€]

R^2_{adj}	0.77			
Variables	**Non-standardized Coefficients**		**Standardized Coefficients**	**p-value**
	Coefficients	**Standard Error**		
(Constant)	8144.653	322.269	-	<0.001
A_{win} [m^2]	623.820	3.193	0.655	<0.001
HDD_{env} [K d]	4.168	0.044	0.394	<0.001
A_{env} [m^2]	51.595	0.517	0.355	<0.001
CDD_{gl} [K d]	0.188	0.002	0.313	<0.001
η_H [-]	-7907.077	171.868	-0.149	<0.001
η_C [-]	-1707.607	45.831	-0.121	<0.001
$\kappa_i \cdot A_{tot}$ [kJ K^{-1}]	-0.315	0.015	-0.075	<0.001
CDD_{env} [K d]	-9.302	0.412	-0.098	<0.001
$Y_{ie,\,env}$[W m^{-2} K^{-1}]	345.962	91.726	0.014	<0.001

5. CONCLUSIONS

The application of dynamic simulation to a large number of configurations for energy retrofitting of buildings have been analysed to identify the predominant factors, for each retrofitting interventions and for different starting cases, in determining the energy need and the total cost of investment. The building simulations have put in evidence some highlights after confirmed by the statistical analysis. In general the energy retrofitting of buildings is particularly economically onerous if the government financial incentives are not taken into account. In particular some economical savings have been found in Milan, very few in Rome and almost null in Messina. The effectiveness of the retrofit interventions adopted are more relevant for climate with predominant heating need. In this climate the interventions that are the most economically advantageous are the insulation of opaque envelope and the convenience of retrofit measures depends very much on the geometrical ratio S/V. The substitutions of windows, which in Italy is the most common refurbishment action, often does not involve an economic advantage whatever is the location.

With the use of statistical analysis some of this considerations have been confirmed and can be generalized. The analysis has put in evidence the weight of some parameters on determining a variation of the Net Present Value of the total cost (investment plus running costs), $NPV_{IC,}$ for each case. The regressive model elaborated shows that the main influencing parameters for the NPV_{IC} are the windows area, the opaque envelope area, and the HDD_{env} for the opaque envelope and the CDD_{gl} for the glazing.

NOMENCLATURE

Symbols

A	area	(m^{2})
c	specific heat	(kJ kg^{-1} K^{-1})
CDD	cooling degree days	(K d)
d	layer thickness	(m)
g	total solar transmittance	(-)
h	surface heat transfer coefficient	(W m^{-2} K^{-1})
HDD	heating degree days	(K d)
I	global irradiance	(W m^{-2})
IC	investment cost	(€ m^{-2})
NPV	Net Present Value	(€)
Δt	time shift	(h)
SHGC	solar heat gain coefficient	(-)
S	disperding envelope surface	(m$^{2)}$
U	thermal transmittance	(W m^{-2} K^{-1})
V	conditioned volume of building	(m^{3})
Y	dynamic thermal transmittance	(W m^{-2} K^{-1})

Greek symbols

α	solar absorptance	(-)
η	efficiency or COP	(-)
κ	areal heat capacity	(J m^{-2} K^{-1})
λ	thermal conductivity	(W m^{-1} K^{-1})
ρ	density	(kg/m^{3})
θ	temperature	(°C)

Subscripts

c	cooling
e	external
env	opaque envelope
f	frame
fl	floor
gl	glazings
h	heating
H	horizontal
i	internal
r	radiative
s	surface
sol-air	solar-air
sky	sky dome
tot	total
V	vertical
W	wall
win	window

REFERENCES

Bolattürk, A., 2008, Optimization insulation thickness for building walls with respect to cooling and heating degree-hours in the warmest zone of the Turkey, *Build.Environ.*, vol. 43: p.1055-1064.

Heiselberg, P., Brohus, H., Hesselholt, H., Rasmussen, H., Seinre, E., Thomas, S., 2009, Application of sensitivity analysis in design of sustainable buildings, *Renew.Energ.*, vol. 34: p.2030-2036.

Gasparella et al., 2011, A. Gasparella, G. Pernigotto, F. Cappelletti, P. Romagnoni, P. Baggio, Analysis and modeling of window and glazing systems energy performance for a well insulated residential building, *Energy Build.*, vol. 43: p. 1030-1037

Jaffal, I., Inard, C., Ghiaus, C., 2009, Fast method to predict building heating demand based on the design of experiments, *Energy Build.*, vol. 41: p.669-677.

Kaynakli, O., 2008, A study on residential heating energy requirement and optimum insulation thickness, *Renew. Energ.*, *Int. J. Refrig.*, vol. 33: p.1164-1172.

Kaynakli, O., 2012, A review of the economical and optimum thermal insulation thickness for building applications, *Renew. Sust. Energ. Rev.*, vol. 16: p.415-425.

Lawrence Berkeley National Laboratory, 2011, *WINDOW 6.3*, *User Manual*, Windows & Daylighting Group, Building Technologies Program, Environmental Energy Technologies Department, Laurence Berkeley National Laboratory, Berkeley, USA.

Lollini, Rr., Barozzi, B., Fasano, G., Meroni, I., Zinzi, M., 2006, Optimization of opaque components of the building envelope. Energy, economic and environmental issues, *Build. Environ.*, vol. 41: p.1001-1013.

Özkan, D.B., Onan, C., 2011, Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey, *Appl. Energ.*, vol. 88: p.1331-1342.

Solar Energy Laboratory, 2005, TRNSYS 16 a Transient Simulation Program, University of Wisconsin, Madison, Wisconsin.

U.S. Department of Energy, 2011, Getting Started with EnergyPlus Basic Concepts Manual, the University of Illinois and the University of California.

Yildiz, Y., Arsan., Z. D., 2011, Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates, *Energy*, vol. 36: p.4287-4296.

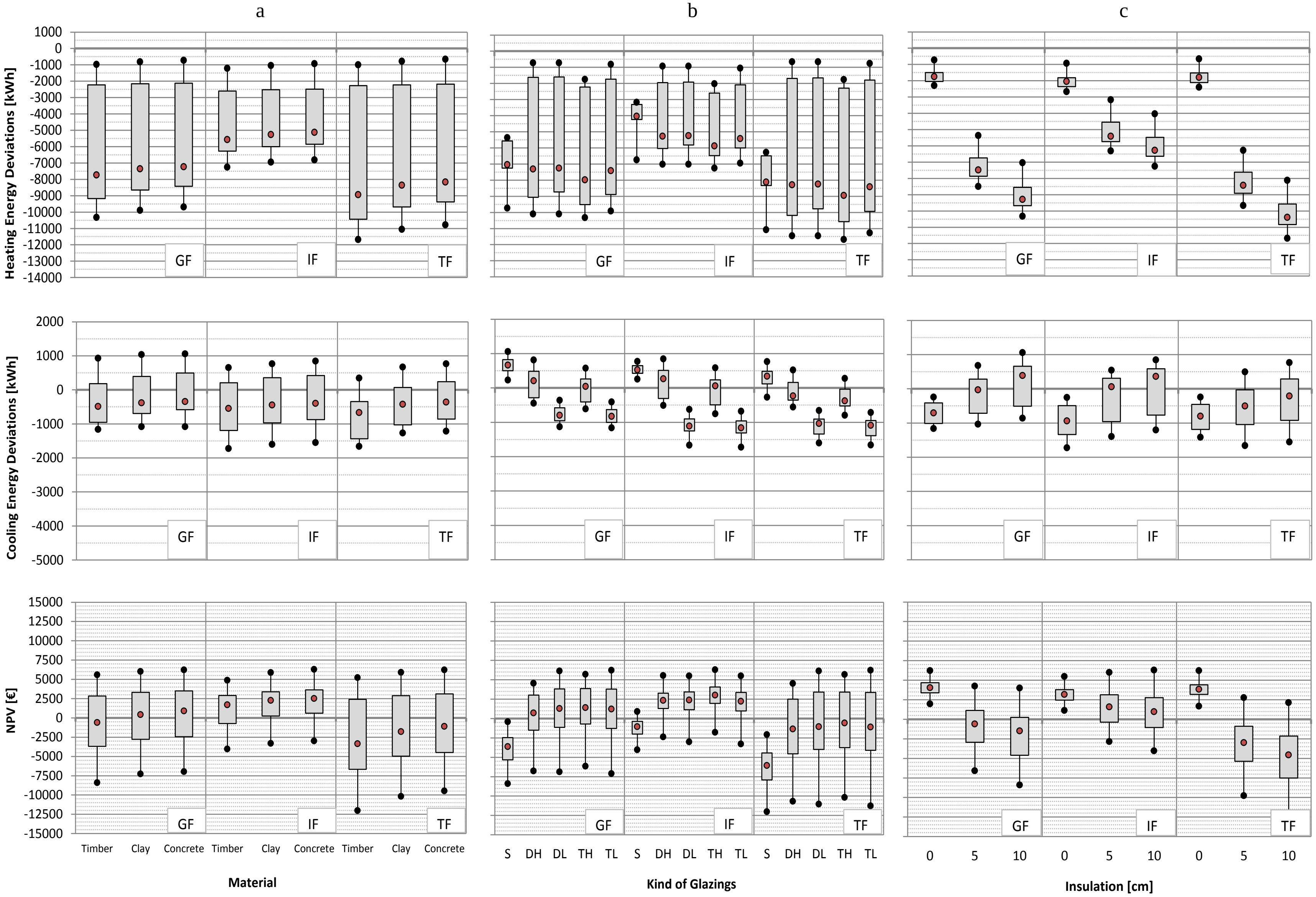

Figure 1: Deviation in heating and cooling energy needs and differential *NPV* for the case of Milano with smaller windows grouped by structures' material (a), kind of glazing (b) and insulation thickness (c).

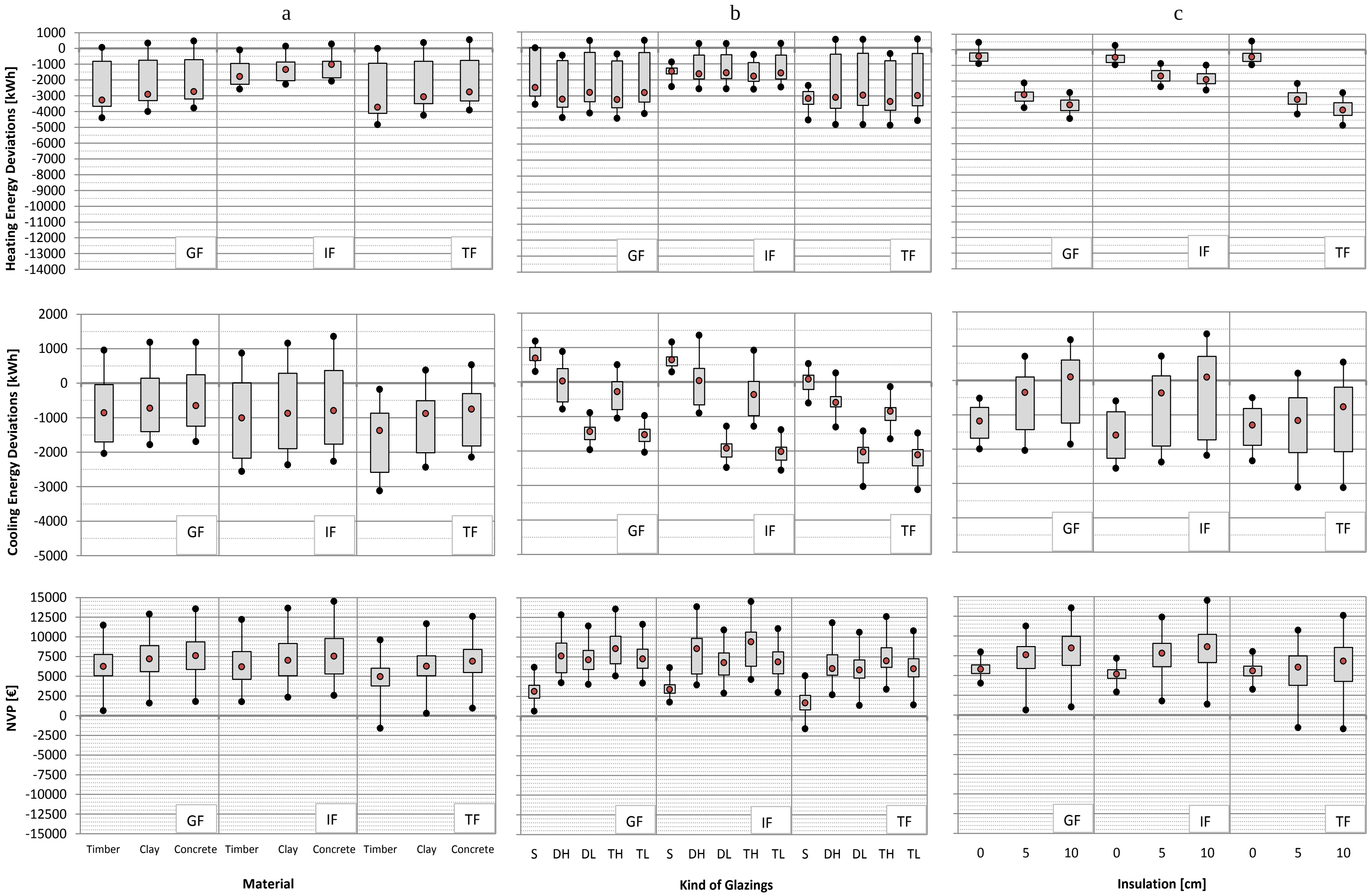

Figure 2: Deviation in heating and cooling energy needs and differential *NPV* for the case of Messina with smaller windows grouped by structures' material (a), kind of glazing (b) and insulation thickness (c).