ANALYSIS OF COST-EFFECTIVE MEASURES FOR BUILDING REFURBISHMENT

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ABSTRACT

This paper presents the analysis of different measurements for the energy retrofit of residential buildings. A number of 54 reference cases have been composed from a simplified building model of 300 m^3 and they have been simulated in three different Italian climatic conditions. On the reference cases 14 retrofitting interventions on the opaque envelope have been evaluated considering the monthly energy needs and the total cost of the investment. The results of the 2430 configurations have been elaborated through three approaches: a differential descriptive analysis, the cost-effective evaluation according to the recent Delegated Regulation EU 244/2012, and the statistical method.

INTRODUCTION

The Directive 31/2010 (European Commission, 2010), known as EPBD *recast*, imposed that within the 2020 all the new buildings will be near zero-energy buildings. Moreover the Member States shall adopt measures and implement policy strategies in order "to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings". According to the new approach of the EPBD *recast*, the minimum energy performance requirements have to be found calculating the cost-optimal levels. Recently the European Commission has published the Commission Delegated Regulation EU 244/2012 in order to indicate the general criteria for the cost-optimisation procedure.

The International Energy Agency underlines how the residential sector is the major responsible in energy consumption (about the 40% of the total energy demand) and it has recently approved the Annex 56 activity with the purpose of analysing the potentiality of building renovation in energy saving (IEA, 2012). In Italy, according to the Population and Housing Census (Italian National Institute of Statistics, 2011), two-third of the building stocks were built before the adoption of the first energy legislations (Law no. 373 of 1976), with energy performance significantly 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 designs.

The improvement of the building envelope could reduce significantly its global energy consumption, by reducing the thermal losses during the heating season and the solar gains through the windows during the cooling season. At the same time the use of a more efficient system can lead to consistent energy savings. One of the main issue in building energy refurbishment is to evaluate and compare different solutions in order to respect the law requirements. To fix this requirements the Member States should compare different combinations of retrofit measures in order to find the optimal one, both for energy saving and for economical reasons. This kind of methodology, called cost-optimal analysis, can be applied also on a single building: this way different refurbishment strategies could be compared in order to find the optimal cost-effective package of measures. This cost-optimal situation depends on the initial and the boundary conditions.

In literature some the authors have analyzed different envelope interventions considering a large number of variables and combining them: this is the case of the analysis on the optimal thickness of insulation carried out for different buildings characteristics, especially the glazing area and the glazing type (Kaynakli, 2008; Kaynakli 2012; Özkan and Onan, 2011), and under different climatic conditions (Bolattürk 2008; Lollini *et al.* 2006).

Besides this parametrical approach based on an extensive recourse to dynamic simulation codes some authors propose the use of statistical sensitivity analysis in order to analyze the results of dynamic simulation and to find out the most important parameters and the relative weight of them in determining the energy need (Heiselberg, 2009; Jaffal *et al*., 2009; Ylidz and Arsan, 2011).

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 Italian locations (Milan, Rome and Messina) which have been considered as representative of the South Europe climate. Different retrofitting interventions, such as the improvement of insulation level of walls and windows and the introduction of glazings with different solar properties, have been evaluated considering the monthly energy needs and the total cost of the investment. The comparison between the effectiveness of the different interventions, both energetical and economical, has been carried out by means of descriptive statistical analysis. The cost-optimal approach has been applied to some selected cases in order to propose a new evaluation methodology. Finally, the results have been elaborated to identify the predominant factors in determining the Net Present Value of the investment cost, for different contexts by means of the inferential statistical analysis.

REFERENCE CASES AND SIMULATION ASSUMPTIONS

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 K d), Rome (HDD_{20} = 1415 K d) and Messina (HDD_{20} = 707 K d), which represent three Italian main climatic areas (Northern, Central and Southern regions).

A single apartment has been modelled successively considering three different positions in a multi-storey building:

- 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).

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 around 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 layers have been reported in Table 1.

The windows of the reference cases are composed of 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 W m^{-2} K^{-1}). The frame area is the 19.9% of the whole window area. Two glazings sizes, 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.

Table 1
Characteristics of the reference cases

Characteristics of opaque envelope			
	Timber	**Clay**	**Concrete**
d (m)	0.10	0.20	0.30
λ (W m^{-1} K^{-1})	0.13	0.25	0.37
R (m^2 K W^{-1})	0.77	0.80	0.81
κ (kJ m^{-2} K^{-1})	75	150	300
ρ (kg m^{-3})	399	893	1190
c (J kg^{-1} K^{-1})	1880	840	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}		
Ratio A_{gl}/A_{fl}	Size 1: 11.67%		
	Size 2: 23.34%		
Orientation	East / South / West		

The effect of the thermal bridges has been neglected. In fact, their weight 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.

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

162 different reference cases have been defined combining the climates, the geometric characteristics, the boundary conditions of the thermal zones, the three different opaque structures and the orientation of the windows. The energy needs have been calculated by means of the simulation code EnergyPlus 7. 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;
- The simulated HVAC system works according to a temperature band which maintains the indoor air temperature between 20 °C and 26 °C for the whole year. This is particularly important in order to compare the energy needs in different climatic conditions.

RETROFITTING DESIGN PARAMETERS

To improve the thermal performance of the envelope the following refurbishment interventions have been considered (Table 2):

- the application of an external insulation layer with two possible thicknesses (0.05 m and 0.10 m);
- the substitution of the window frame with a thermal break wood/aluminium one (U_f = 1.2 W m^{-2} K^{-1});

Table 2
Retrofitting interventions

OPAQUE ENVELOPE: INSULATION LAYER			
d (m)	λ (W m^{-1} K^{-1})	c (J kg^{-1} K^{-1})	ρ (kg m^{-3})
0.05 0.10	0.04	1470	40

TRANSPARENT ENVELOPE: GLAZINGS		
	U_{gl} (W m^{-2} K^{-1})	SHGC (-)
DH – Double Glazings with high SHGC (4/9/4, krypton, low-e treatment)	1.140	0.608
DL – Double Glazings with low SHGC (6/16/6, krypton, low-e treatment)	1.099	0.352
TH – Triple Glazings with high SHGC (6/12/6/12/6 krypton, low-e treatment)	0.613	0.575
TL – Triple Glazings with low SHGC (6/14/4/14/6 argon, low-e treatment)	0.602	0.343

- 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 heat transfer 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 3
Thermal characteristics of the refurbished opaque envelope (a vertical wall has been considered)

		Timber	Clay	Concrete
U_W (W m^{-2} K^{-1})	0.00 m	1.061	1.027	1.016
	0.05 m	0.456	0.456	0.448
	0.10 m	0.290	0.288	0.287
Y_{ie} (W m^{-2} K^{-1})	0.00 m	0.885	0593	0292
	0.05 m	0.240	0.127	0.045
	0.10 m	0.129	0.063	0.024
Δt_{ie} (h)	0.00 m	-3.52	-6.29	-10.08
	0.05 m	-5.62	-8.69	-12.40
	0.10 m	-6.76	-9.48	-13.12

RESULTS AND DISCUSSION

Differential descriptive analysis

The 2430 yearly heating and cooling energy needs simulated have been used as input for the economic analysis, considering the costs and the parameters 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 the Lazio Region. The discount factor has been fixed in 4%, expressed in real terms, hence excluding inflation in the calculation because the all the costs/savings are constant and not monetary, according to the Commission Delegated Regulation EU 244/2012. 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 energy price development trends (a part from inflation) nor subsidisation form have been considered in the economical analysis.

A global representation of the energy and economic results are reported in Figure 2, where the boxplots represent the maximum, the minimum, the interquartile range (*IQR*) and the median of all the cases compared. Concerning the heating and cooling energy needs evaluation, the differences between the retrofitted cases and the corresponding reference cases have been considered. Negative values means that the refurbishment actions give energy savings. As regards the economic aspects, the differential Net Present Value (Δ*NPV*) distributions have been represented. The Δ*NPV* represents the discounted difference between the total costs (investments costs plus running costs) related to the cases with retrofits, and the running costs of the corresponding reference cases. Considering all the costs as positive, a negative value of the ΔNPV means that the intervention is economically advantageous, with the discounted savings overbalancing the initial investment.

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) EUR 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) EUR m^{-2}, where x is the insulation thickness	
Investment for 1 m^2 of window	DH	IC_{DH} = 511.81 EUR m^{-2}
	DL	IC_{DL} = 555.77 EUR m^{-2}
	TH	IC_{TH} = 604.62 EUR m^{-2}
	TL	IC_{TL} = 575.31 EUR m^{-2}
Fuel Cost [1]	0.0935	EUR/kWh
Lower Heating Value of the Fuel [2]	32.724	MJ Sm^{-3}
Electricity Cost [1]	0.25	EUR/kWh_{el}
Length of the investment	20	Years
Discount factor	4 %	
HEATING AND COOLING SYSTEM		
Overall base heating efficiency, η_h	80%	
Overall base cooling EER_c, 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

The results have been distinguished with respect to the different envelope materials, type of glazings and to the thicknesses of insulation, distinguishing the three considered locations, the three floor positions and the size of the windows. Figure 2 shows the energy deviations and the values of ΔNPV for the cities of Milan (in blue) and Messina (in yellow) only for the cases with larger windows – because for the smaller ones the main difference is a smaller dispersion, i.e. a smaller *IQR*, of the data for the cooling needs deviations and the ΔNPV (Pernigotto *et al.*, 2012). For Rome the trends are between the other two localities.

From this first analysis some accurate considerations can be drawn:

- the effectiveness of the retrofit interventions adopted is more relevant for climate with predominant heating need;
- the economical efficacy of refurbishment measures seems to be very influenced by the geometrical ratio S/V especially for colder climate;
- the retrofit measures in general give more energy savings and more economical advantages for timber structures than for clay or concrete ones;
- the effect of the different kinds of glazing is strongly related to the SHGC in particular for the cooling needs but the energy improvement often does not involve an economic advantage;
- compared to the cases with smaller windows, for larger windows the retrofit actions on energy reduction tends to become in general more effective from the energy point of view although the investment costs rise;
- the insulation thickness is effective in energy savings in heating predominant locations, where it is also economically beneficial.

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

Cost effective analysis

Selecting a few number of cases a different analysis of the results is presented in Figure 3, where the graphs show the relationship between the Net Present Values and the Primary Energy for the clay-block structure with South-faced smaller windows. In this representation the *NPV* of the investment (following denoted with NPV_{IC}) has been re-calculated, considering the total investment costs of each case (investment plus running costs). The primary energy has been estimated and represented selecting three different system configurations among the 9 considered: the low-efficiency cases in red (η_h=0.64, EER_c=2.4), the base-efficiency cases in white (η_h=0.8, EER_c=3) and the high-efficiency cases in green (η_h=0.96, EER_c=3.6). For the primary energy calculation, the Italian national electrical system efficiency of 45 % has been considered (Autorità per l'energia elettrica e il gas, *Delibera EEN 3/08*).

The reference cases are crossed by a vertical and an horizontal dotted lines which divide the graph plane into four quadrants. A schematic representation is reported in Figure 1 for explicative purpose. With the help of this quadrant subdivision it is possible to find the convenience of the considered measures under energetic and economic point of view. The right upper quadrant, Q_1, defines the non-convenient measures on both aspects, the only case that presents these results is Messina, where retrofit actions examined could worse both the energy behavior of the building and the economic result. The Q_2 identifies the efficient solution under the energetic point of view but not economically convenient. These solutions deliver high level of energy performance but their cost-effectiveness decrease because of the significant investment costs. The cases lying on the lower quadrant on the left, Q_3, are the cost and energy-effective solution, where the investment costs are lower than the value of the resulting benefits and some energy improvements are registered. These cases represent the optimal refurbishment solution and when present, are joined with the reference ones by a dotted line. Finally the lower quadrant on the right, Q_4, identifies the cases where energy measures are economically but not energetically effective: there isn´t any case that is representative of this situation.

Comparing the NPV_{IC} of these solutions with the reference case, it is possible to underline some cases where the NPV_{IC} is equivalent to the reference situation. It could be reasonable and feasible to encourage the achievement of this optimal level through financial incentives by the UE Member States Governments. The linear approximations of these additional investments and their energy effects have been underlined in the graphs by horizontal colored areas (in parallel, also the vertical colored areas representing the additional energy improvements have been reported). For those cases (in Milan) where the neutral NPV_{IC} is much higher than the considered cases, these additional investment areas have been considered not for the neutral NPV_{IC} but for the best measures studied.

Looking at the points disposition it can be seen that in Milan in all the considered situations and in Rome in the *TF* and in the *GF* an optimal refurbishment case can be found between those considered in this study. Moreover in Rome and in Messina the most of the considered cases lie in the quadrant, Q_2, because the interventions are too expensive.

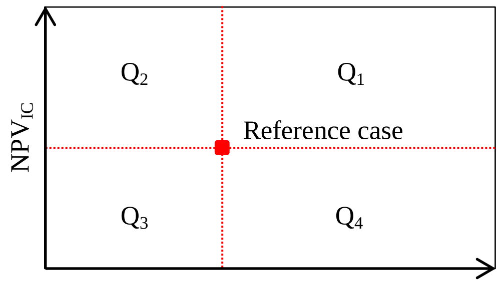

Figure 1 Schematic representation of the NPV-Primary Energy graph.

Statistical inferential analysis

The results of the differential analysis can be confirmed and generalized by inferential statistics, as done in a previous work (Pernigotto *et al.*, 2012). In particular, the inferential statistical technique employed was a multivariate linear regression with a confidence level of 95% and the variables have been selected by means of the stepwise algorithm. The standardized coefficients (i.e., 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) have been considered in order to identify the main influencing parameters.

The considered variables were formuled in order to take into account of the different thermophysical and geometric characteristics of the building envelope, the overall system efficiency and the boundary conditions both for the reference and the retrofitted cases. For instance, we considered:

- the steady (U_{env}) and periodic thermal transmittance ($Y_{ie,env}$) and the time shift ($\Delta t_{ie,env}$) of the walls, the internal heat capacity ($\Delta\kappa_i \cdot A_{tot}$) and the dispersing walls areas (A_{env}) for describing the opaque envelope;
- the glazings thermal transmittance (U_{gl}) and *SHGC* and the windows areas (A_{win}) for modelling the transparent envelope;
- the overall heating (η_H) and cooling (η_C) systems efficiency for the system;
- the heating degree days (HDD_{env}) and the cooling degree days (CDD_{env}) for the opaque envelope, calculated as in Pernigotto *et al.* (2012) and the heating degree days (HDD_{gl}) and the cooling degree days (CDD_{gl}) for the glazings as in Gasparella *et al.*, (2011) for taking into account of the different external solicitations on the envelope.

The main influencing parameter for the NPV_{IC} has been found to be the windows area, followed by the opaque envelope area, the HDD_{env} for the opaque envelope and by the CDD_{gl} for the glazings. The higher are the performances of the systems, the lower are the NPV_{IC}. The inferential analysis confirmed the findings of the differential descriptive analysis.

CONCLUSIONS

In this work different approaches to the retrofit optimization problem have been studied. By means of an extensive application of the dynamic simulation the predominant factors and the most cost and energy effective reburbishment measures have been identified for the different starting cases considered. These results have been then confirmed by the statistical regressive analysis. For a selected number of cases a cost effective analysis has been implemented in order to identify the optimal solution from both economic and primary energy point of view. The combination of the different methodology can give a good representation of the refurbishment potential of the building stock. In fact with the general extensive simulation it is possible to identify the main factors to consider for the retrofit measures, and the further specific detailed cost effective analysis allows to select the optimal combination of them.

NOMENCLATURE

SYMBOLS

A	area	(m^2)
c	specific heat	($J\ kg^{-1}\ K^{-1}$)
CDD	cooling degree days	(K d)
d	layer thickness	(m)
HDD	heating degree days	(K d)

IC	investment cost	(€ m^{-2})
NPV	Net Present Value	(€)
Δt	time shift	(h)
R	thermal resistance	(m^2 K W^{-1})
SHGC	solar heat gain coefficient	(-)
S	dispersing 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	(kJ m^{-2} K^{-1})
λ	thermal conductivity	(W m^{-1} K^{-1})
ρ	density	(kg m^{-3})
	SUBSCRIPTS	
c	cooling	
e	external	
env	opaque envelope	
f	frame	
fl	floor	
gl	glazings	
h	heating	
H	horizontal	
i	internal	
s	surface	
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.

Pernigotto, G., Penna, P., Cappelletti, F., Gasparella, A., Extensive Utilization Of Dynamic Simulation For Sensitivity Analysis And Optimization Design Of Refurbishment Measures, *Proc. Of International High Performance Buildings Conference at Purdue*, July 16-19.

European Commission, 2010, Directive 2010/31/EU of the European Parliament and of the Council), Official Journal of European Union, L 153/13, 18/06/2010

European Commission, 2012, Commission Delegated Regulation EU 244/2012, Official Journal of European Union, L81/18, 20/03/2012

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

IEA, 2012, Annex 56 Cost-Effective Energy & CO2 Emissions Optimization in Building Renovation. http://www.ecbcs.org/annexes/annex56.htm

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.

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

Mitchell, J.W., Beckman, W.A. 1995. Instructions for IBPSA Manuscripts, SEL, University of Wisconsin, Madison USA.

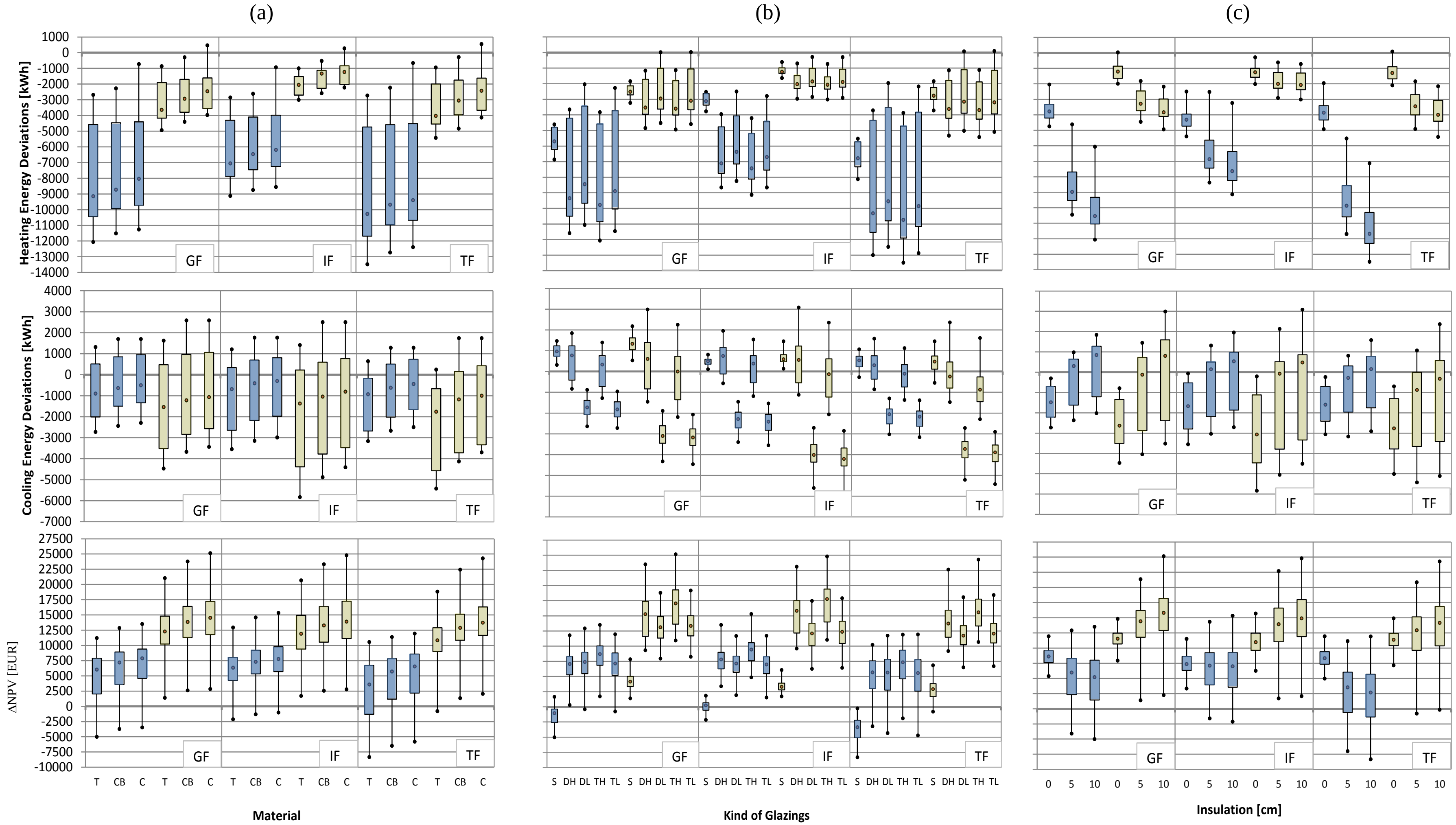

Figure 2: Deviation in heating and cooling energy needs and differential *NPV (ΔNPV)* for the case of Milan (blue) and Messina (yellow) with larger windows grouped by structures' material (a), kind of glazing (b) and insulation thickness (c).

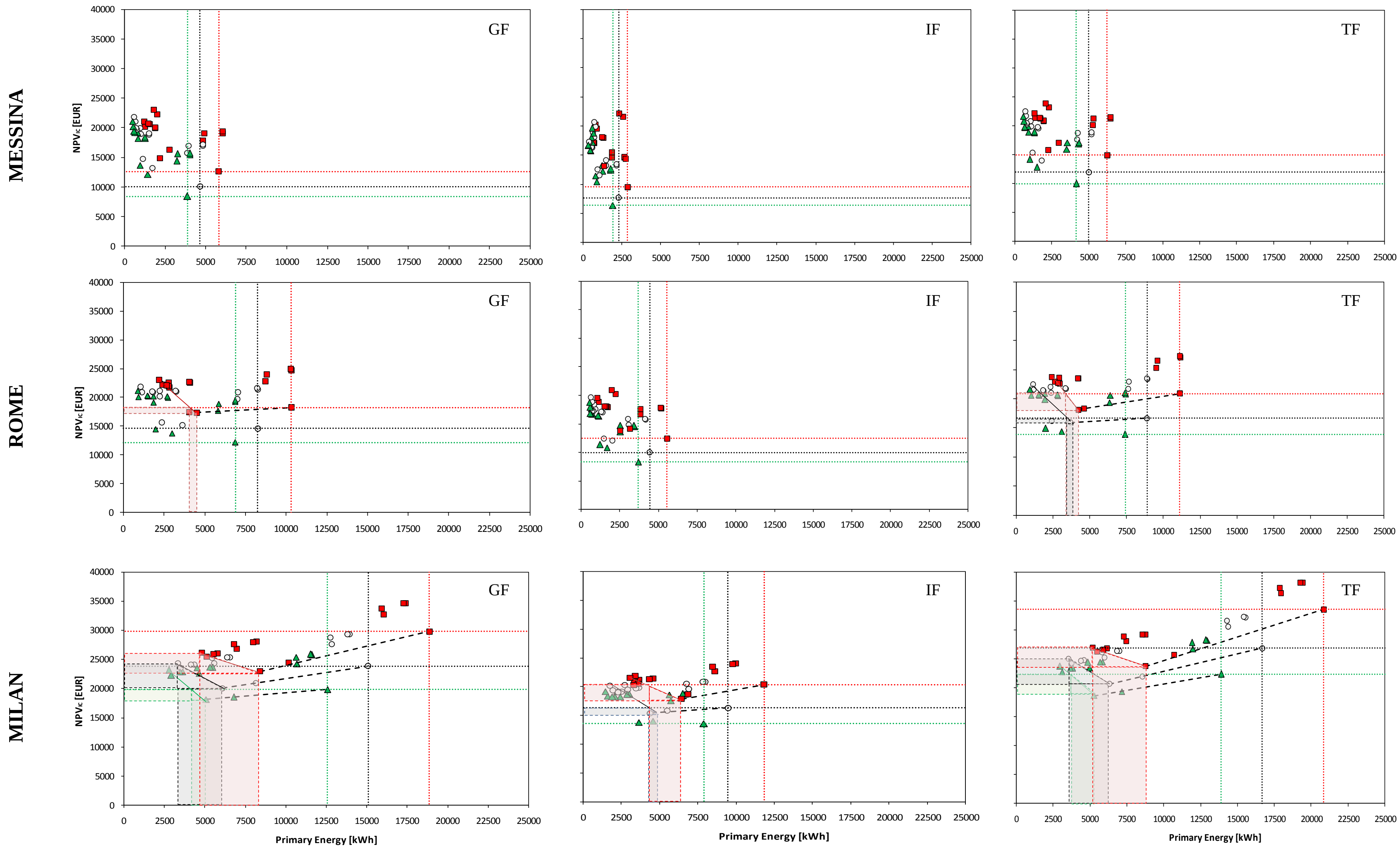

Figure 3: NPV_{IC} [EUR] and Primary Energy [kWh] for the three locations and the three floors analysed for the cases with a clay block structure and smaller South-oriented windows. In red the worst system efficiency, in green the best one and in black the base case.