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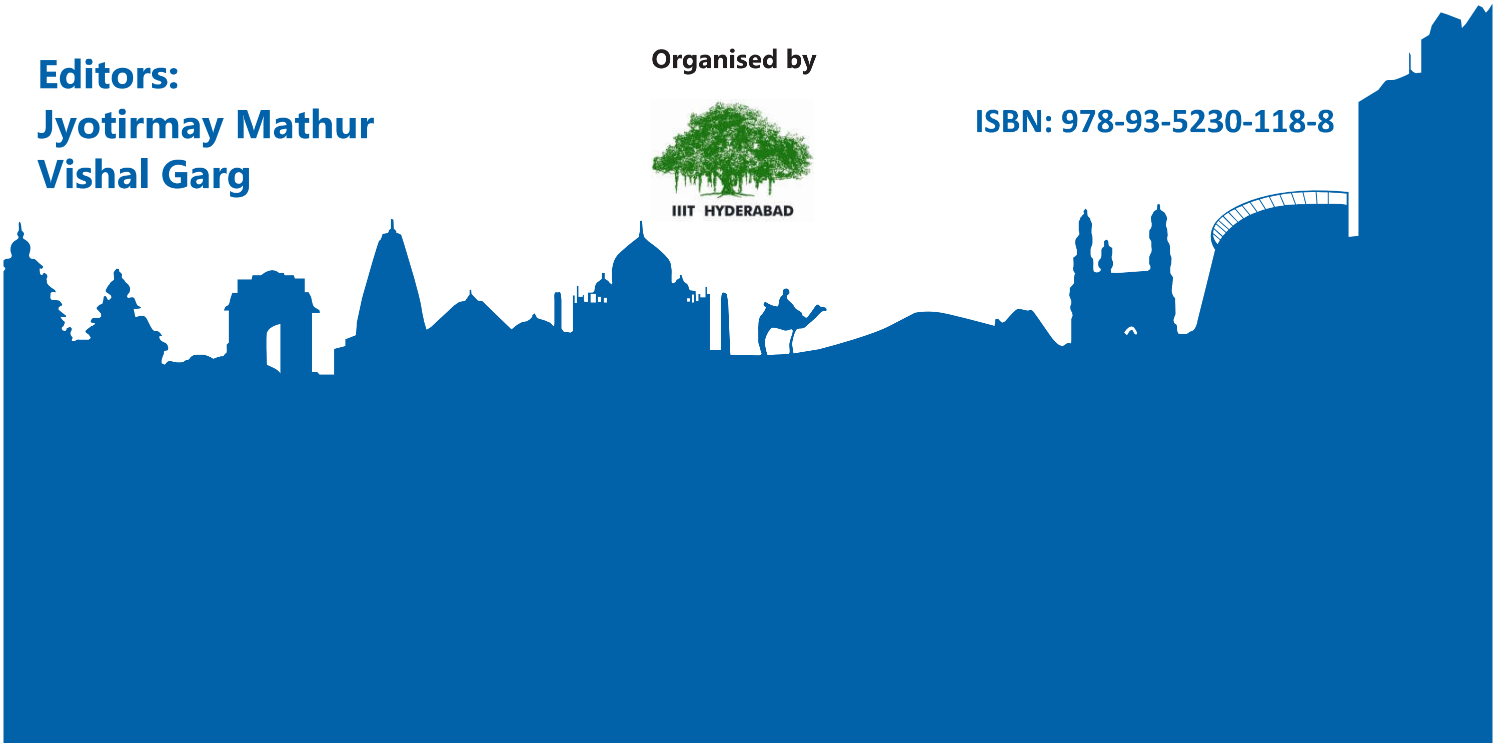

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COST-OPTIMAL ANALYSIS OF ITALIAN OFFICE BUILDINGS THROUGH THE APPLICATION OF A QUASI-STEADY STATE MODEL VALIDATED BY DETAILED DYNAMIC SIMULATION

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ABSTRACT

In the present paper a methodology for identifying the cost-optimal levels of minimum energy performance requirements (according to Directive 2010/31/EU), already introduced in a previous work (Corrado et al., 2014), is applied to Italian reference office buildings, different in the glazed area.

The optimal energy efficiency measures, resulting from the application of a quasi-steady state numerical model, are then modelled by means of a dynamic simulation tool and the deviations are discussed. The aim is to validate the simplified model and to pave the way for future researches on cost optimality by applying energy performance simulation.

INTRODUCTION

The comparative methodology framework according to Directive 2010/31/EU

European Directive 2010/31/EU on the energy performance of buildings, also known as *EPBD recast* (European Union, 2010), requires Member States to take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view to achieve cost-optimal levels. Member States shall calculate cost-optimal levels of minimum energy performance requirements using a comparative methodology framework.

The comparative methodology framework has been established by the Commission Delegated Regulation No. 244/2012 (European Union, 2012a) which supplements the Directive 2010/31/EU in order to provide the Member States with a common procedure to calculate cost-optimal levels of minimum requirements for the energy performance of buildings and building components.

A cost-optimal level is the energy performance (EP) level which leads to the lowest global cost during the estimated economic lifecycle, taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building, earnings from energy produced), and disposal costs, where applicable.

The comparative methodology consists of the following activities:

1. definition of reference buildings (RBs), representative of the building stock according to specific criteria (e.g. building use, climatic conditions, age, size),
2. definition of different packages/variants of energy efficiency measures (EEMs) for each reference building (RB),
3. calculation of the primary energy demand resulting from the application of the EEM packages/variants to a RB,
4. calculation of the global cost resulting from the application of the EEM packages/variants to a RB in its expected economic lifecycle,
5. identification of the cost-optimal level of energy performance of and the related optimal EEM package/variant for each RB.

Calculation methods of the reference building energy performance

The guidelines that accompany the Regulation (European Union, 2012b) include information to help Member States to apply the comparative methodology at the national level.

The calculation of the energy demand of a reference building considering different energy efficiency measures consists in determining the annual total global energy use in terms of primary energy, including energy use for heating, cooling, ventilation, domestic hot water and lighting in non-residential buildings.

It is recommended that Member States use CEN standards for their energy performance calculations. In this regard, the energy balance of the building and its systems is the basis of the procedure. For instance, the main calculation procedure of the building energy need for space heating and cooling consists of the following steps, according to EN ISO 13790 (European Committee for Standardization, 2008):

- choice of the type of calculation method,
- definition of boundaries and thermal zones of the building,
- definition of internal conditions and external input data (e.g. climatic data),

- calculation of the energy need for each time step and thermal zone,
- consideration of the interactions between thermal zones and/or systems.

A choice of three different methods is suggested in the CEN standards for the first step, as follows:

- a fully prescribed monthly quasi-steady state calculation method,
- a fully prescribed simple hourly dynamic calculation method,
- calculation procedures for detailed dynamic simulation methods.

For the purpose of the cost-optimal calculation, the guidelines accompanying the Regulation (European Union, 2012b) give the following recommendations to achieve reliable results:

- performing the calculations by using a dynamic method,
- defining boundary conditions and reference use patterns in conformity with the calculation procedures, unified for all the calculation series for each reference building,
- providing the climatic data used,
- define thermal comfort (e.g. indoor set-point temperatures for heating and cooling) for each reference building.

Several studies have been carried out on this topic.

The cost-optimal calculations can be performed by means of several procedures; among these, the sequential search-optimisation technique is widely applied, as for instance in Christensen et al. (2004) and in Hamdy et al. (2013).

As concerns the methodology for the energy performance calculation in the cost-optimal analysis, both quasi-steady state and dynamic simulation models are widely applied. In some cases, both of them are used for evaluating the behaviour of different building and system components (Baglivo et al., 2015).

Most of the national methods used in the Member States to enforce the Directive 2010/31/EU are based on monthly or seasonal models under stationary conditions (Maldonado, 2013). Several research studies are instead based on the application of dynamic simulation tools, like the ones presented by Corgnati et al. (2013), Ferrara et al. (2014), Ganiç et al. (2014), Becchio et al. (2015), Ascione et al. (2015).

The comparison between the quasi-steady state method and the dynamic simulation method in the cost-optimal analysis should be further investigated, with the purpose of establishing whether a simplified simulation model correctly performs the cost/benefit analysis and identifying the causes of the deviations in the results.

Objective and steps of the work

The present paper provides an application of the cost optimality by using the CEN simplified method (European Committee for Standardization, 2008). Following the guidelines of the Regulation No. 244/2012 (European Union, 2012b), the methodology introduced in a previous work (Corrado et al., 2014), that allows to identify the cost-optimal levels for the Italian building stock, is applied to two office buildings, different in the glazed area.

For each reference building, several measures for the building envelope and the technical systems, each characterised by different energy efficiency levels, are defined. The measures are applied together as in a major energy refurbishment.

The energy performance calculations are carried out by means of a quasi-steady state numerical model (Italian Organisation for Standardisation, 2010-2014), the global cost is calculated according to EN 15459 (European Committee for Standardization, 2007b), while the cost optimisation procedure is based on a sequential search-optimisation technique considering discrete options (Corrado et al., 2014).

The optimal energy efficiency measures resulting from the analysis are then applied in *EnergyPlus* considering the same reference buildings. The deviations in the energy performance results of the two models are finally discussed.

It must be stressed that the objective of the work is not to compare the cost-optimal calculations by means of two different methods, since the only cost-optimal solution is identified by the quasi-steady state model. Nevertheless the comparison of the results of the two calculation models applied to the same solution, in terms of energy and cost, is useful for validating the simplified model and paving the way for future research activities aimed at investigating different approaches in cost-optimality.

In order to make the results of the two models (dynamic and quasi-steady state) comparable, the modelling procedures are made consistent and the boundary conditions, including climatic data, ventilation profiles, internal heat gains, etc., are made uniform.

SIMULATION

Definition of reference buildings and energy efficiency measures

The reference buildings were selected among those introduced in a previous work (Corrado et al., 2013). The office buildings differ from each other only in the glazed area. A lower (OFF_01) and a higher (OFF_02) window area to total envelope area ratio are considered.

The location of the buildings is Milano (Italy, climatic zone E – 2404 HDD).

The main geometrical data of the reference buildings are reported in Table 1.

Table 1
Geometrical data of the reference buildings

RB	V_g [m^3]	A_f [m^2]	A_{env}/V_g [m^{-1}]	A_w/A_{env} [-]	N. OF UNITS
OFF_01	4340	1740	0.40	0.20	56
OFF_02				0.44	

Each energy efficiency measure (EEM) applied to the reference buildings in the cost-optimisation procedure is defined through appropriate technologies and parameters; e.g. the *U*-value for the thermal insulation of the building envelope, the energy efficiency (either η_{gn} or *COP* or *EER*) for the heat generators, the collectors area (A_{coll}) for the thermal solar system, the peak power (W_{PV}) for the photovoltaic system, etc.

For each measure, up to three energy efficiency options (EEOs) or levels, were defined. They are comparable with those established by the Italian Government for the implementation of the EU comparative methodology framework at national level. The most efficient EEOs match the levels identified for the nearly-zero energy buildings target. The Italian building code also requires minimum levels of the Renewable Energy Ratio (RER) in new buildings and in major renovations; for this reason, fit measures have been set up in the analysis.

The initial investment cost associated to each EEO was got either from extensive market surveys or from official national databases (DEI, 2011).

The energy efficiency measures and options are listed in Table 2 with the associated investment costs. They do not vary for the two offices.

Table 2
Energy efficiency measures and options, and related investment costs for the reference buildings

EEM		EEO 1	EEO 2	EEO 3
Wall insulation (on external surface)	U_{wl} [Wm^{-2}K^{-1}]	0.29	0.25	0.20
	cost [€ m^{-2}]	29	35	47
Roof insulation	U_r [Wm^{-2}K^{-1}]	0.26	0.23	0.20
	cost [€ m^{-2}]	36	42	51
Lower floor insulation	U_f [Wm^{-2}K^{-1}]	0.29	0.24	0.20
	cost [€ m^{-2}]	21	26	38
Windows	U_w [Wm^{-2}K^{-1}]	1.60	1.30	-
	cost [€ m^{-2}]	382	435	-
Solar shading device	Type of louvres	Fixed	Movable	-
	τ_{sh} [-]	0.40	0.40	
	cost [€ m^{-2}]	40	105	-
Chiller *plus*	*EER* [-]	3.5	4.0	5.0
	cost [€]	27 500	33 000	40 700
heat generator for space heating and domestic hot water *or*	η_{gn} [-]	0.88	0.934	1.03
	cost [€]	5 500	6 600	9 900
Heat pump for space heating, space cooling and domestic hot water	*COP* [-]	2.3	2.7	3.1
	EER [-]	2.1	2.5	2.9
	cost [€]	33 000	38 500	44 000
Thermal solar system	A_{coll} [m^2]	2	4	6
	cost [€]	1 600	3 000	5 000
Photovoltaic system	W_{PV} [kW]	3	5	8
	cost [€]	9 000	15 000	24 000
Heat recovery	η_{rec} [-]	0.7	0.9	-
	cost [€]	9 600	12 000	
Lighting system, defined according to EN 15193 (European Committee for Standardization, 2007a)	W_{lgt} [Wm^{-2}]	13	4.7	4.6
	F_o - F_c	0.9 - 0.9	1 - 1	0.8 - 0.9
	cost [€ m^{-2}]	30	36	45

Not all the energy efficiency measures are applicable together, because some of them are inconsistent with the others (e.g. a chiller *plus* a heat generator is inconsistent with a combined heat pump), as clearly indicated in Table 2.

Cost-optimisation procedure by applying a quasi-steady state calculation method

The energy performance of the reference buildings was calculated according to the Italian technical specification UNI/TS 11300 (Italian Organisation for Standardisation, 2010-2014), which specifies a quasi-steady state calculation method based on the standard EN ISO 13790 (European Committee for Standardization, 2008) to determine the net energy need for space heating and cooling. The method considers the steady state balance of heat losses (transmission and ventilation) and heat gains (solar and internal) evaluated in average monthly conditions. The dynamic effects on the net heating and cooling energy needs are taken into account by introducing dynamic parameters, i.e. the utilization factors, that accounts for the mismatch between transmission *plus* ventilation heat losses and solar *plus* internal heat gains.

The boundary conditions applied in the model are described in the “Options for the consistency of the models” subsection.

For each building end use considered, the total primary energy has been calculated as the sum of non-renewable and renewable primary energy. The primary energy factors were assumed equal to 1.1 for natural gas and 2.4 for electricity.

The global cost analysis was performed applying EN 15459 (European Committee for Standardization, 2007b), with the following assumptions:

- calculation time of 20 years, considering a financial scenario,
- real interest rate fixed at 4%,
- costs of electricity and natural gas derived from the National Authority for Electricity and Natural Gas (AEEG),
- annual increase in gas price of 2.8% and in electricity price according to the guidelines (European Union, 2012b),
- annual maintenance costs variable from 0% to 4% of the investment cost depending on the technology,
- technical lifespan of building elements fixed at 20 years, of systems variable from 15 to 20 years.

The residual value of each building component at the end of the calculation period, considering its lifespan and referred to the starting year, has been taken into account.

The cost optimisation was carried out by means of a procedure based on a sequential search-optimisation technique considering discrete options (i.e. the EEOs listed in Table 2), as described in detail in Corrado et al. (2014). This procedure refers to the model developed by Christensen et al. (2006).

The optimal level of the annual primary energy use for heating, cooling and domestic hot water, the corresponding actualized global cost and the related optimal values of the energy efficiency measures are reported in the “Discussion and result analysis” section.

Dynamic simulation method

The dynamic simulation was conducted by means of *EnergyPlus* (version 7.2). The building thermal zone calculation method of *EnergyPlus* is an air heat balance solution method, based on the assumptions that, by default, the temperature of the air in the thermal zone and of each surface are uniform, the long and short-wave irradiation is uniform, the surface irradiation is diffusive and the heat conduction through the surface is one-dimensional.

The geometrical model of the buildings and the technical system modelling were developed in *Simergy*, which is a “Building Energy Modeling” (BEM) front-end to the *EnergyPlus* simulation engine.

The cost-optimal energy efficiency options resulting from the application of the quasi-steady state calculation method previously described were kept in the dynamic simulation of the reference buildings.

The boundary conditions applied in the dynamic simulation model are consistent with those used in the simplified method, as described in the following subsection.

Options for the consistency of the models

In order to compare the energy needs obtained with the two models (dynamic and quasi-steady state), a study was carried out to make the modelling procedures consistent. The considered settings and boundary conditions applied were defined as follows:

- The climatic data of Milano used in the dynamic simulation are part of the data set known as “International Weather for Energy Calculation” (IWEC). The monthly average values of the daily outdoor air temperature and solar radiation were applied to the quasi-steady state calculation method.
- A constant value of 6 Wm^{-2} was adopted for internal heat gains in the simplified model, obtained as the mean value of the daily profile used in the dynamic model. The same approach was followed for the ventilation flow rate, equal to an average value of 0.27 m^3s^{-1} (including the heat recovery efficiency).
- In the solar heat gains evaluation, the factor of time using shadings, weighted on the incident solar irradiation, has been evaluated by

EnergyPlus by an hourly simulation, for each exposure and for each locality, as the ratio of the sum of hourly irradiance values greater than 300 Wm^{-2} and the sum of all irradiance values for the whole month. In the simplified method, the monthly values of the factor are based on the same assumption, even if they are provided regardless of the location and climate.

- In the quasi-steady state calculation model, the thermal transmittance of transparent components was evaluated in accordance with EN ISO 10077-1 (European Committee for Standardization, 2006) starting from glass and frame thermal transmittances. In *EnergyPlus*, each window was defined by the physical parameters of glass and frame to obtain the same value of global thermal transmittance. The same procedure to derive the window total solar energy transmittance and the reduction factor of shading was performed. Moreover the glass component in *EnergyPlus* has some additional characteristics not considered in the simplified model, such as colour, spectral features, etc.
- In the simplified model, the monthly average values of the sky temperature, which allow to calculate the extra heat flow due to thermal radiation to the sky from each building element, were derived from the weather file of *EnergyPlus*.
- The sizes of the heating and cooling systems were determined by means of the winter and summer design days.
- The comparison between the two models is carried out by considering the mean monthly values of the net energy need taking into account both the heating and the cooling mode.
- The system operation period defined in the simplified model has been also applied in the detailed model for the calculation of the primary energy use.
- The DHW and the lighting energy consumptions have been determined according to UNI/TS 11300 and to EN 15193 respectively; the results are not considered in the comparison between the two models.

DISCUSSION AND RESULT ANALYSIS

Each optimal solution corresponds to a specific set of values of energy efficiency options. As shown in Table 3, the same optimal set is determined both for OFF_01 and for OFF_02. The initial investment cost, the energy cost and the operational cost of the optimal solution, with the share of each on the global cost, are shown in Table 4 for the two offices.

Table 3
Optimal energy efficiency options for the reference buildings (OFF_01, OFF_02)

EEM	**Parameter**	**Value**
Wall insulation (on external surface)	U_{wl} [$Wm^{-2}K^{-1}$]	0.29
Roof insulation	U_r [$Wm^{-2}K^{-1}$]	0.26
Lower floor insulation	U_f [$Wm^{-2}K^{-1}$]	0.29
Windows	U_w [$Wm^{-2}K^{-1}$]	1.60
Solar shading device	Type of louvres - τ_{sh} [-]	Fixed - 0.40
Chiller *plus*	*EER* [-]	3.5
Heat generator for space heating and DHW	η_{gn} [-]	1.03
Thermal solar system	A_{coll} [m^2]	2
Photovoltaic system	W_{PV} [kW]	3
Heat recovery	η_{rec} [-]	0.9
Lighting system	W_{lgt} [Wm^{-2}] F_o - F_c	4.6 0.8 - 0.9

The results of the cost-optimisation procedure through the quasi-steady state method for the analysed buildings are shown in Figure 1, for the OFF_01, and in Figure 2, for the OFF_02.

Figures 1 and 2 show the sets of partial optimum points related to different applications of the optimization procedure to the reference buildings, starting from different sets of EEOs. The white point represents the optimal solution, expressed through the global cost and the energy performance (i.e. the annual total global primary energy). The grey area identifies the optimal range, in qualitative terms, according to the guidelines of the European Commission (European Union, 2012b). This range has been defined assuming a cost variation of ±2%.

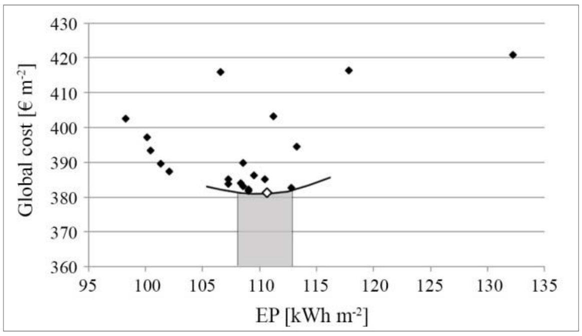

Figure 1 Partial optimum points and optimal range for the building OFF_01

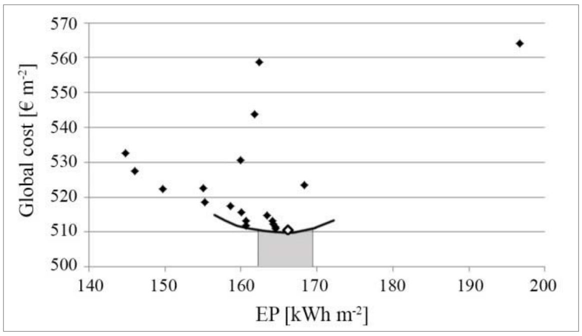

Figure 2 Partial optimum points and optimal range for the building OFF_02

Table 4

Breakdown of the global cost of the optimal solution

RB	**Investment**	**Energy**	**Operation and maintenance**
OFF_01	175 € m^{-2} *(46 %)*	167 € m^{-2} *(44 %)*	39 € m^{-2} *(10 %)*
OFF_02	246 € m^{-2} *(48 %)*	215 € m^{-2} *(42 %)*	49 € m^{-2} *(10 %)*

The results of the quasi-steady state method and of the dynamic simulation consequent to the application of the optimal EEOs are shown in Figures 3-6.

Figures 3 and 4, for OFF_01 and OFF_02 respectively, show the comparison of the net energy needs for space heating and space cooling.

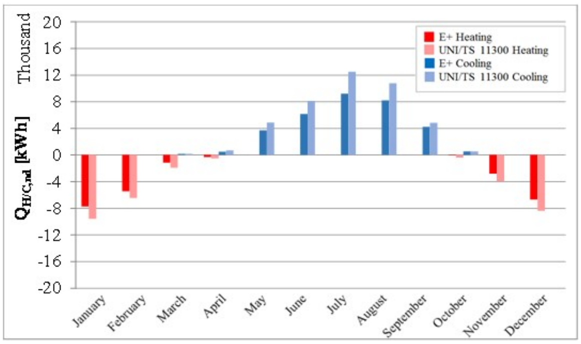

Figure 3 OFF_01. Comparison of the two models as regards the net energy need for heating and cooling

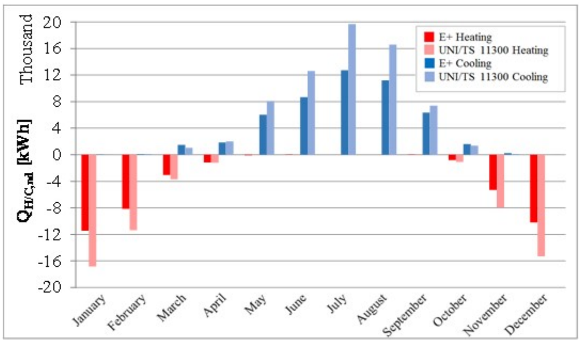

Figure 4 OFF_02. Comparison of the two models as regards the net energy need for heating and cooling

Figures 5 and 6 show the total global primary energy and the global cost for OFF_01 and OFF_02 respectively, evaluated by means of the quasi-steady state model (UNI/TS 11300) and of the dynamic simulation tool (E+).

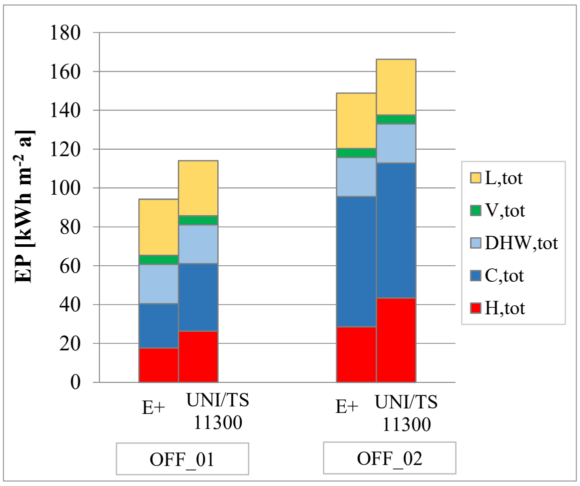

Figure 5 Comparison of the two models on the total global primary energy for OFF_01 and OFF_02

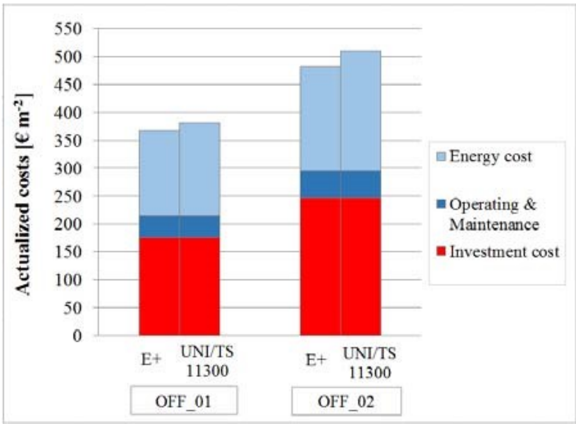

Figure 6 Comparison of the two models on the global cost for OFF_01 and OFF_02

Although the application of the above described options to make the input data consistent, significant deviations still are shown between the two calculation models. The main reason is the different calculation structure of the models.

The heat balance terms linked to solar radiation and to internal heat sources are considered purely convective in the quasi-steady state model, while the detailed model takes into account the absorption phenomena and the internal heat exchange by infrared radiation between the inner surfaces. Moreover, in the simplified model, the air temperature is used in place of the operative temperature and the nonlinear effects on the surface heat transfer coefficients are not considered.

A different modelling approach for the heat exchanges to the ground and to the unconditioned spaces is also used in the two models.

Another factor that can cause deviations between the two models is the building thermal inertia and its effect on its dynamic behaviour. The quasi-steady state model uses simplified dynamic parameters, like the utilisation factors, to account for the mismatch between heat transfer and heat gain. This simplified approach can yield an inaccurate assessment of the energy need, as highlighted by Corrado et al. (2007).

The quasi-steady model also makes use of simplifications in the evaluation of the technical systems performance, by applying a monthly or seasonal efficiency and considering a linear correlation between the efficiency and the load factor of the heat generator. Conversely, the dynamic method takes into account the effect of the fluctuations of the external conditions and the of heat load of the building on the heat generator efficiency. The discrepancy between the quasi-steady state and the dynamic methods due to the different modelling of the thermal system behaviour is highlighted in many works, as for instance in Rey et al. (2007).

Figure 6 shows a slight deviation in the global cost between the two models; the discrepancy is only referred to the energy cost, as the same EEOs are considered in both models.

CONCLUSION

A new methodology that allows an accurate and robust detection of the cost-optimal solutions among a large number of different energy efficiency measures and packages of measures has been developed.

Nevertheless, significant deviations are detected in the comparison between the results of the quasi-steady state model and of the dynamic simulation, despite the same package of measures has been applied in both the models. A further validation of the simplified model is required to delimit cases in which it can be applied with sufficient accuracy.

Despite the significant deviations in the energy assessment, the results point out that the global cost differs of less than 50 € m^{-2} between the two models. Nevertheless, being the energy cost around 50% of the global cost, it is pointed out that the discussion on the most suitable method for the energy assessment cannot leave aside from an analysis of the uncertainties of the investment costs and of the energy cost trends.

The future research activity will include a full adaptation of the cost-optimal procedure to accurate dynamic simulation. This will also aim at comparing the cost-optimal solutions among different packages of energy efficiency measures coming from the different models.

NOMENCLATURE

A = area [m^2]
COP = coefficient of performance [-]
EER = energy efficiency ratio [-]
F = factor [-]
Q = energy [Wh]
U = thermal transmittance [Wm^{-2}K^{-1}]
V = volume [m^3]
W = power [W]
η = efficiency [-]
τ = transmission coefficient [-]

Subscripts

C = cooling
c = control
coll = (solar) collectors
env = envelope
f = floor
g = gross
gn = generation (system)
H = heating
lgt = lighting
nd = need (energy)
o = occupancy
PV = photovoltaic (system)
r = roof
rec = heat recovery (system)
sh = (solar) shading
w = window
wl = wall

Acronyms
DHW= domestic hot water
EEM = energy efficiency measure
EEO = energy efficiency option
EP = energy performance
E+ = Energy Plus, dynamic model
L = lighting
RB = reference building
UNI/TS 11300 = quasi-steady state model
V = ventilation

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