On the Cost-Optimal Design: Comparison of Quasi-Steady-State and Dynamic Simplified Methods of Calculation of H/C Energy Needs

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Abstract

The Directive 2010/31/EU promotes the improvement of the energy performance of buildings within the European Union, by taking into account indoor climate requirements and cost-effectiveness. Thus, the cost optimisation is one of the main objectives of the EU regulatory framework concerning the energy performance of both new buildings and existing buildings subject to refurbishment actions. When assessing the cost-optimal levels of energy performance, the calculation of the energy needs is usually carried out by means of CEN standards or equivalent national calculation methods, based either on steady-state or on dynamic simplified models. However, many research studies have pointed out the limitations of the steady-state approach, especially for high performance buildings.

The aim of this work is to study how the calculation method – quasi-steady or dynamic - of the energy needs for heating and cooling, impacts on the final optimal design. This is done through the application of a cost-optimal procedure to a single-family house located in Milan. The building energy needs for space heating and cooling are calculated by means of the quasi-steady-state monthly method specified by the Italian standards and the simplified hourly dynamic model of ISO 13790. The performance of the thermal systems is then assessed by means of the national standards (UNI/TS 11300), while the global cost is evaluated by means of EN 15459. Several design options with increasing levels of energy efficiency are applied to the case study.

We compare the cost-optimal solutions derived from the application of the two methods, and discuss the reasons for the deviations.

1. Introduction

1.1 Research Studies on Cost-Optimal Design

The Guidelines accompanying the Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31/EU, introduce a comparative methodology framework for calculating cost-optimal levels (European Union, 2012). It gives the possibility to compare energy efficiency measures on the basis of their energy performance and costs.

The Guidelines indicate three calculation methods of energy performance: monthly quasi-steady-state calculation method, simple hourly dynamic calculation method, and detailed dynamic simulation methods. The literature concerning the Cost Optimal Analysis (COA) shows that the quasi-steady-state method has been applied both to the design of new nZEB (Kurnitski et al., 2011) and to the refurbishment of existing buildings (Corrado et al., 2016a), while the detailed dynamic simulation method was applied in similar cases, often using TRNSYS (Ferrara et al., 2016) or EnergyPlus (Becchio et al., 2015). Comparisons of cost optimality results between the quasi-steady-state method and the detailed dynamic simulation are carried out in other works, as for instance in Corrado et al. (2015). The simple hourly dynamic calculation method has been used less than the other methods in COA studies; it is taken into account, for instance, when the analysis is focused on the energy delivered and the matching with renewable sources (Testi et al., 2016).

The Guidelines indicate two methods to deal with the iterations between the building and its systems: a holistic approach, where the heat gains from the technical building system are considered in the calculation of the energy need, or a simplified approach, where the recovered heat losses of the system are obtained by fixed conventional recovery factors. The holistic approach is more common in the dynamic models.

1.2 Aim

This paper aims to investigate how different calculation methods for heating and cooling energy needs influence the results of a cost-optimal analysis. A case study is taken into account and two out of the three calculation methods indicated by the Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 are applied. The two methods considered are the quasi-steady-state monthly method, and the simple hourly dynamic method of ISO 13790 standard (ISO, 2008). The study considers the parameters of cost and energy performance.

2. Calculation Models and Optimization Procedure

2.1 Quasi-Steady-State Method

The quasi-steady-state calculation method is presented in ISO 13790 standard (ISO, 2008). It is based on the monthly balance of heat losses (transmission and ventilation) and heat gains (solar and internal) assessed in monthly average conditions. The dynamic effects on the net energy needs for space heating and space cooling are taken into account by introducing a utilization factor that takes into account the time mismatch between transmission *plus* ventilation heat losses and solar *plus* internal heat gains, and that considers an ideal control system which allows overheating or undercooling. The utilisation factor depends on the time constant of the building, on the ratio of heat gains to heat losses and on the occupancy/system management schedules.

The space heating and cooling energy need for each month is calculated as:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} \cdot Q_{gn} \qquad (1)$$
$$Q_{C,nd} = Q_{gn} - \eta_{C,ls} \cdot Q_{C,ht} \qquad (2)$$

where, $Q_{H/C,nd}$ is the space heating/cooling energy need, $Q_{H/C,ht}$ is the total heat transfer (transmission *plus* ventilation), Q_{gn} is the total heat gains (internal *plus* solar), $\eta_{H,gn}$ is the utilization factor of heat gains for heating mode, and $\eta_{C,ls}$ is the utilization factor of heat losses for cooling mode.

The quasi-steady-state monthly method specified in the Italian standards (UNI/TS 11300) (UNI, 2014) is applied in the present work.

2.2 Simple Hourly Method

The simple hourly dynamic method is described in Annex C of ISO 13790 standard (ISO, 2008). It consists in a simplification of the heat transfer between outdoor and indoor environment based on a similarity between the thermal behavior of the analyzed building and a resistance – capacitance network made up of 5 resistances and 1 capacitance (5R1C). The schematics of the model is reported in Fig. 1 where, θ_{air} is the indoor air temperature, θ_s is the temperature given by the mix of mean, radiant and indoor air temperature, θ_m is the temperature of the capacitive mass node, θ_e is the outdoor air temperature, θ_{sup} is the supply air temperature, H_{ve} is the ventilation heat transfer coefficient, $H_{tr,is}$ is the heat transmission coefficient between the air node and the surface node, $H_{tr,w}$ is the transmission heat transfer coefficient of doors, windows, curtain walls and glazed walls, $H_{tr,op}$ is the transmission heat transfer coefficient of opaque components, C_m is the building fabric internal heat capacity, Φ_{ia}, Φ_{st}, Φ_m are the internal and solar heat gains, $\Phi_{H/C,nd}$ is the heating or cooling heat load.

The indoor air temperature (θ_{air}), at each time step, is calculated as:

$$\theta_{air} = \frac{H_{tr,is} \cdot \theta_s + H_{ve} \cdot \theta_{sup} + \Phi_{ia} + \Phi_{H/C,nd}}{H_{tr,is} + H_{ve}} \qquad (3)$$

Summing the $\Phi_{H/C,nd}$ per each time step adopted by the model (1 h), the heating/cooling energy needs during the analyzed period is obtained ($Q_{H/C,nd}$).
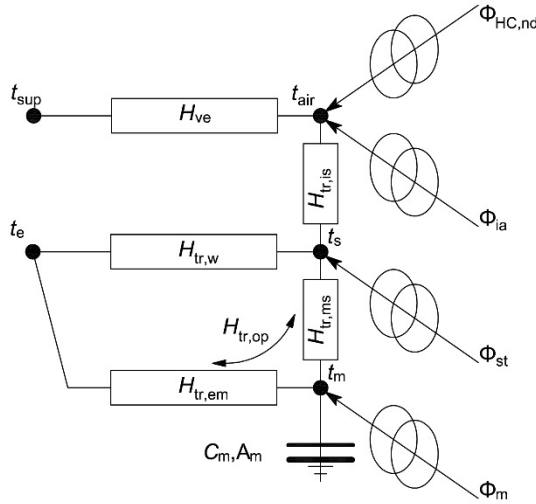
Fig. 1 – Schematic representation of the simple hourly method (ISO, 2008)

2.3 The Cost-Optimal Approach

The cost-optimal solution consists in a package of energy efficiency measures characterised by the lowest global cost compared to a reference package (starting point of the optimization). In the present work, the cost optimisation procedure was based on a sequential search-optimisation technique considering discrete options or levels of energy efficiency measures, as described in detail in Corrado et al. (2014). This procedure refers to the model developed by Christensen et al. (2006). The procedure allows to identify a sequence of "partial optimums", each one obtained from the previous one by modifying all the parameters that characterize the levels of each energy efficiency measure one at a time.

The global cost analysis was performed by applying EN 15459 standard (CEN, 2007). The global cost (C_{gl}) is expressed as in Eq. (4). It is directly linked to the duration of the calculation period t. The calculation, referred to the starting year t_0, may be performed by a component or system approach, considering the initial investment (C_I), and, for every component or system j, the annual costs (C_a) and the discount factor (R_{disc}) for every year i (referred to the starting year), and the final value Val_F.

$$C_{gl}(t) = C_I + \sum_j \left[\sum_{i=1}^{t} \left(C_{a,i}(j) \cdot R_{disc}(i) \right) - Val_{F,t}(j) \right] \quad (4)$$

3. Case Study and Input Data

3.1 The Case Study

The case study is a single-family house built in the period 1976–1990.

It is a reference building selected within the IEE-TA-BULA project. The main geometric and construction data of the building are shown in Table 1, while the features of its thermal systems are listed in Table 2.

Table 1 – Main geometric and construction data of the case study

Geometric data			Construction data		
V	[m³]	725	U_{wl}	[W m⁻²K⁻¹]	0.76
$A_{f,n}$	[m²]	199	$U_{fl,lw}$	[W m⁻²K⁻¹]	0.98
A_{env}/V	[m⁻¹]	0.69	$U_{fl,up}$	[W m⁻²K⁻¹]	0.97
A_w	[m²]	24.9	U_w	[W m⁻²K⁻¹]	2.80
No. storeys	-	2	$g_{gl,n}$	[-]	0.75

Table 2 – Features of the thermal systems of the case study

Space heating (H) and DHW (W) systems			Space cooling system		
Radiators	$\eta_{H,e}$	0.94	Heat terminal units	$\eta_{C,e}$	0.97
Central distribution	$\eta_{H,d}$	0.91	Zone temp. control	$\eta_{C,c}$	0.94
Gas standard boiler for H	$\eta_{H,g}$	0.85	Zone distribution	$\eta_{C,d}$	1.00
Gas standard boiler for W	$\eta_{W,g}$	0.80	Split system (100 % load)	EER	2.35

3.2 The Energy Efficiency Measures

The cost-optimal approach considered a whole renovation of the building. The energy efficiency measures (EEMs) concern both the fabric and the technical building systems (see Table 3): EEMs from 1 to 5 consider the envelope; EEMs 6 and 7 stands for the replacement of the technical building systems for space cooling and for combined space heating and domestic hot water preparation by means of different technologies (condensing boiler, biomass generator, district heating, air-to-water heat pump). The energy production from renewables is taken into account by EEMs 8 (solar collectors for DHW)

and 9 (PV panels), while EEM 10 considers the heat recovery ventilation system. Finally, EEM 11 refers to the use of an advanced control for space heating. Several levels of performance (EELs) for each EEM were considered; for each level, the thermal parameter value and the referred specific cost are listed in Table 3; the data results from a market survey (Corrado et al., 2016b). The costs exclude 22 % VAT but include extra-costs for lathing and technical building system adjustments.

Table 3 – Energy efficiency measures (EEMs) and related performance levels (EELs) and costs

No.	EEM	Parameter		EEL			
				1	2	3	4
1	External wall thermal insulation	U_{wl}	[W m^{-2}K^{-1}]	0.30	0.26	0.20	
		C_I/A_{wl}	[€ m^{-2}]	25.75	28.86	35.10	
2	Upper floor thermal insulation	$U_{fl,up}$	[W m^{-2}K^{-1}]	0.30	0.25	0.20	
		$C_I/A_{fl,up}$	[€ m^{-2}]	11.70	15.60	21.06	
3	Lower floor thermal insulation	$U_{fl,lw}$	[W m^{-2}K^{-1}]	0.30	0.25	0.20	
		$C_I/A_{fl,lw}$	[€ m^{-2}]	23.40	27.30	31.20	
4	Window thermal insulation	U_w	[W m^{-2}K^{-1}]	1.90	1.80	1.40	1.16
		C_I/A_w	[€ m^{-2}]	113.88	119.57	124.21	150.50
5	Solar shading system	τ_s	[-]	0.40	0.35		
		$C_I/A_{shadings}$	[€ m^{-2}]	50.00	70.00		
6	Chiller	EER	[-]	2.90	3.50	4.00	
		C_I	[€ m^{-2}]	1638	1872	2028	
7	Combined generator for heating, DHW, and appropriate emission system	$\eta_{gn,Pn,H+W}$ or COP	[-]	1.10	0.90	0.99	4.45
		C_I	[€]	2100	11700	3120	6000
8	Thermal solar system	A_{coll}	[m^2]	3.00	3.40	4.00	6.60
		C_I	[€]	3042	3354	3666	5148
9	PV system	W_P	[kW]	1.00	2.00	3.00	4.00
		C_I	[€]	1716	3090	4680	6240
10	Heat recovery ventilation system	η_{ve}	[-]	0.90			
		C_I	[€]	1716			
11	Heating control system	$\eta_{H,c}$	[-]	0.995			
	* Cost computed in EEM 7	C_I		*			

3.3 Input Data

The calculation was performed for the Milan location (2404 HDD). The weather database of the Italian Thermotechnical Committee was used.

Concerning the building energy performance evaluation: the values of the thermal transmittance of the opaque components already includes the effect of thermal bridges; the internal heat capacity of the building was calculated according to ISO 13786; the external obstacles were not considered; the heat transfer through the unheated spaces was calculated by means of the adjustment factors $b_{tr,U}$. Concerning the user behaviour, the following input data and assumptions were used:

- the sensible internal heat gains and the ventilation flow rate were defined by hourly schedule; the weekly mean values are respectively 4.5 W m^{-2} and 0.04 m^3 s^{-1},
- the solar shadings were used when the incident solar radiation on the transparent components was higher than 300 W m^{-2},
- two different operational modes were considered for the heating season: a continuous and an intermittent schedule related to the user's presence. In the first case the setpoint was fixed at 20 °C; in the latter case 14 hours a day of operational time were set at 20 °C, and the setback was fixed at 16 °C,
- the cooling setpoint was fixed at 26 °C.

In the global cost analysis, a financial perspective calculation was adopted, without considering subsidies. The calculation was performed over 30 years, with a real interest rate of 3 %. The energy costs as well as the energy trend scenarios, the annual maintenance costs and the technical lifespan of building components and systems used in the calculation process derived from previous studies (Corrado et al., 2016b).

The energy performance was calculated in accordance with ISO 52000-1 and it is expressed in terms of non-renewable primary energy (EP_{nren}). The renewable and non-renewable primary energy factors were assumed according to the Italian regulation. The electricity from PV panels is considered as a reduction of the monthly electrical energy demand, while the exported electrical energy is not considered.

3.4 Consistency options

In order to compare the two models, some consistency options were applied as follows: the monthly values of the outdoor air temperature and of the incident solar radiation derived from the correspondent hourly input data; in the quasi-steady-state method the use of the solar shadings was performed by means of the weighted fraction of the time $f_{sh,with}$, calculated from the hourly values of the simple dynamic method; the sensible internal heat gains and the ventilation flow rate in the monthly method were assumed equal to the mean value of the weekly profile used in the hourly method. Finally, the performance of the thermal building systems was assessed by means of the national standards (UNI/TS 11300, parts 2, 3 and 4) that evaluate the technical building systems performance on a monthly basis. It has to be noted that the hourly variability of the thermal building systems performance might affect the cost-optimal solution choice, however this effect is not considered in the present work.

4. Results

Fig. 2 shows the energy needs for heating and cooling of the case study before retrofit, in continuous operational mode. As a general observation, if the quasi-steady state results are taken as a reference, it can be noticed that the simple hourly method underestimates the energy use for heating and overestimates the energy use for cooling.
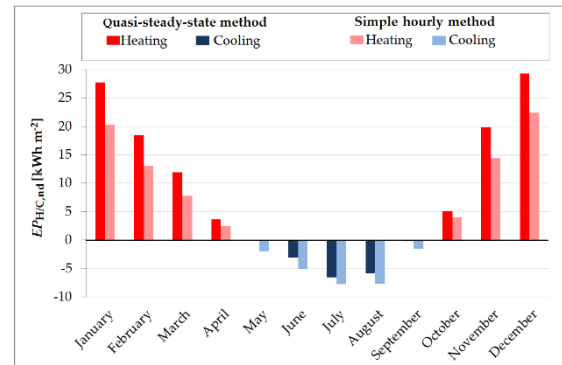

Fig. 2 – Building energy needs for space conditioning before the retrofit

The results of the cost-optimization application are reported in Table 4, in terms of energy efficiency measures and performance levels.

As regards the monthly model, in case of intermittent heating the set-point temperature for the calculation is the same as for the normal heating mode, according to mode B of ISO 13790 (ISO, 2008); that is because the time constant of the building is greater than three times the duration of the longest reduced heating period. For that reason, the energy needs and consequently the cost-optimal solution, do not change with the heating operational mode. In case of quasi-steady-state method, the optimal retrofit considers the thermal insulation of the opaque components by 0.08-0.10 m additional insulating material, the use of external movable shadings in tissue, the installation of thermostatic valves and of wall heat recovery ventilation units in combination with PV.

Table 4 – Cost-optimal packages of measures

No.	EEM	Parameter	Ante retrofit	Cost-optimal packages of measures		
				Quasi-steady-state method	Simple hourly method	
				Continuous / Intermittent mode	Continuous mode	Intermittent mode
1	External wall thermal insulation	U_{wl} [W m^{-2}K^{-1}]	0.76	0.26	0.30	0.30
2	Upper floor thermal insulation	$U_{fl,up}$ [W m^{-2}K^{-1}]	0.97	0.30	0.30	0.30
3	Lower floor thermal insulation	$U_{fl,lw}$ [W m^{-2}K^{-1}]	0.98	0.30	0.30	0,98
4	Window thermal insulation	U_w [W m^{-2}K^{-1}]	2.80	2.80	2.80	2.80
5	Solar shading system	τ_s [-]		0.40	0.40	0.40
6	Chiller	EER [-]	2.35	2.35	4.00	4.00
7	Combined generator for heating, DHW	$\eta_{gn,Pn,H+W}$ or COP [-]	0.85	0.85	0.85	0.85
8	Thermal solar system	A_{coll} [m^2]				
9	PV system	W_P [kW]		2.00	2.00	2.00
10	Heat recovery ventilation system	η_{ve} [-]		0.90		
11	Heating control system	$\eta_{H,c}$ [-]	0.85	0.995	0.995	0.995

When the cost-optimal solution is investigated by means of the simple hourly method, it can be noticed that retrofit measures are generally oriented to the reduction of the energy use for space cooling: lower additional thermal resistance of the opaque wall with respect to the quasi-steady-state method, natural ventilation and substitution of the old splits with more efficient ones. Finally, the additional thermal resistance of the first floor facing the unconditioned space (EEM 3 of Tab. 4) is not considered an optimal retrofit measure when the intermittent operational mode is used in the simple hourly method.

Fig. 3 shows the energy, the investment and the operating and maintenance costs of the building without retrofit and for the cost-optimal solutions. In case of no refurbishment, only the energy and the operating and maintenance costs occur. Results show that, despite different values of the global cost before the refurbishment (650 € m^{-2} in case of a monthly evaluation, 567 € m^{-2} and 524 € m^{-2} for the hourly method with continuous or intermittent heating setpoints respectively), the deviation of the cost-optimal solutions between the two calculation methods is negligible (maximum deviation of 5 € m^{-2} between quasi-steady-state and intermittent

simple hourly model). In particular, the costs for operating and maintenance are similar for all the optimal solutions (115-119 € m^{-2}), while the energy cost and the investment cost counterbalance one another.
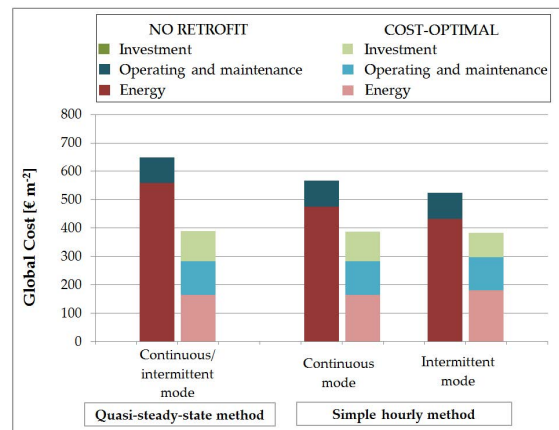

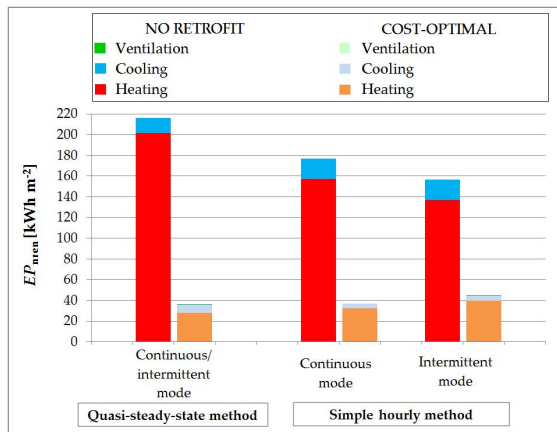Fig. 3 – Global cost, no retrofit and cost-optimal solutions

Fig. 4 – Non-renewable primary energy performance, no retrofit and cost-optimal solutions

Fig. 4 shows the non-renewable energy performance of the cost-optimal solutions compared with the building before the retrofit, calculated by means of the two methods. The cost-optimal approach allows to reduce the non-renewable primary energy use from 71 % by the intermittent mode of the simple hourly method to 83 % by the quasi-steady-state method.

Despite different values of the energy performance of the existing building (216 kWh m^{-2} for monthly method, 177 kWh m^{-2} and 157 kWh m^{-2} for the hourly method with continuous or intermittent heating setpoints respectively), the cost-optimal EP_{nren} is in between 37 kWh m^{-2} of the monthly and the continuous hourly models, and 45 kWh m^{-2} of the intermittent hourly model. The non-renewable energy use for heating is increased in the hourly method (especially with the intermittency mode) because of the minimization of the global cost. Thus, the higher energy cost with respect to the monthly model is counterbalanced by a lower investment cost (Fig. 3) due to the choice of minor additional thermal insulation material and the absence of heat recovery ventilation systems. As well, the different EER values between the cost-optimal solutions of the quasi-steady-state and the simple hourly methods (EEM 6) justify the deviation in $EP_{C,nren}$.

5. Conclusion

The paper presents the application of two different calculation methods for the heating/cooling energy needs in compliance with ISO 13790 to the cost optimization analysis. The analysed methods are the quasi-steady-state and simple hourly.

Results show that the cost-optimal set of energy efficiency measures is different if the quasi-steady-state or the simple hourly method is applied. Moreover, when the hourly model is used, a change in the operational schedule of the heating system (continuous or intermittent mode) entails a different set of cost-optimal retrofit solutions. Nevertheless, similar values of non-renewable energy performance and global cost among several refurbishment solutions, can be found despite the use of different calculation methods.

Nomenclature

Symbols

A	Area (m^2)
$b_{tr,U}$	Correction factor for unconditioned space (-)
C_I	Investment cost (€)
C_m	Heat capacity (J·K^{-1})
COP	Coefficient of performance (-)
EER	Energy efficiency ratio (-)
EP	Energy performance (kWh·m^{-2})
f	Factor (-)
g_{gl}	Total solar energy transmittance (-)
H	Heat transfer coefficient (W·K^{-1})
Q	Thermal energy (Wh)
U	Thermal transmittance (W·m^{-2}K^{-1})
V	Volume (m^3)
W_p	Peak power (kW)
η	Efficiency (-) / utilisation factor (-)
θ	Temperature (°C)
$τ_s$	Solar transmittance coefficient (-)
Φ	Heat flow (W)

Subscripts/Superscripts

a	Air / annual
C	Space cooling
c	Heat control (subsystem)
coll	Solar collectors
d	Heat distribution (subsystem)
e	External / heat emission (subsystem)
env	Building envelope
f, fl	Floor

g	Heat generation (subsystem)
gl	Global
gn	Heat gains
H	Space heating
ht	Heat transfer
I	Investment
i	Internal
ls	Heat losses
lw	Lower
n	Net, normal
nd	Need (energy)
nren	Non-renewable
op	Opaque (component)
Pn	Nominal power
sh	Shading
sup	Supply (air)
tr	Transmission (heat transfer)
up	Upper
ve	Ventilation
W	Domestic hot water
w	Window
wl	Wall

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