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The application of EN ISO 52016-1 to assess building cost-optimal energy performance levels in Italy

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A B S T R A C T

In Italy, the cost-optimisation calculation procedure, based on the comparative methodology framework established by the Commission Delegated Regulation 244/2012 to derive minimum energy performance requirements of buildings, was firstly applied by means of a monthly quasi-steady-state calculation method based on EN ISO 13790. The introduction of the new EN ISO 52016-1 simplified hourly calculation method determined the possibility of testing the new assessment procedure. The aim of this work is to analyse the deviation between the monthly and hourly calculation methods in the assessment of the building energy needs for space heating and cooling and in the selection of cost-optimal solutions. The cost-optimisation analysis was hence performed on a group of buildings representative of the Italian building stock. The results of the monthly and hourly methods in terms of cost-optimal levels and packages of energy efficiency measures were then compared. Results show limited variations in the resulting global cost, while differences in the cost-optimal packages of energy efficiency measures are not negligible. A sensitivity analysis of the main economic parameters was carried out, pointing out the main influencing factors.

1. Introduction

1.1. The comparative methodology framework of directive 2010/31/EU

Directive 2002/91/EC (EPBD) (European Commission, 2002), replaced by Directive 2010/31/EU (EPBD recast) (European Commission, 2010), later amended and supplemented by Directive 2018/844 (European Commission, 2018a), defined the principles regarding the improvement of the energy performance of buildings. In the EPBD recast (European Commission, 2010), Member States are requested to determine minimum requirements for the energy performance of buildings with a view to achieve cost-optimal levels. For this purpose, the Directive introduces a comparative methodology framework with the aim of determining reference requirements for national regulations. The comparative methodology was established by the Commission Delegated Regulation No. 244/2012 (European Commission, 2012a), in which the specifications for the application of the methodological framework are presented from both the technical and the economic perspectives.

The cost-optimal level is defined as the level of energy performance that leads to the lowest global cost during the estimated economic lifecycle of the building (European Commission, 2010). The lowest cost is determined by accounting for energy-related investment, maintenance, operating (e.g., energy costs), and disposal costs. Besides the specific costs for the different energy carriers, the energy costs considered in the global cost calculation strongly depends on the energy demand of the analysed building, and consequently on its determination. The Guidelines supporting the Commission Delegated Regulation No. 244/2012 (European Commission, 2012b) specify three different calculation methods applicable for the determination of the building energy needs, namely monthly quasi-steady-state, simplified dynamic hourly, and detailed dynamic methods. According to the review carried out by Ferrara et al. (2018), detailed dynamic methods (such as EnergyPlus, TRNSYS, and IDA ICE) are used in 58% of research works on the application of the comparative methodology framework in Europe. Plausibly, this is since the Commission Delegated Regulation (European Commission, 2012b) recommends the use of dynamic methods to achieve reliable results. Nonetheless, most of the legislative applications for the determination of

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Nomenclature

Quantities

A	area (m^2)
COP	coefficient of performance (–)
EER	energy efficiency ratio (–)
F	factor (–)
NPV	Net Present Value (€)
P	lighting power density ($W\ m^{-2}$)
PMV	Predicted Mean Vote (%)
PPD	Predicted Percentage of Dissatisfied (%)
Q	thermal energy per unit conditioned floor area ($kWh\ m^{-2}$)
U	thermal transmittance ($W\ m^{-2}\ K^{-1}$)
W	electrical power (kW)

Greek symbols

η	efficiency (–)
θ	temperature (°C)

Subscripts/Superscripts

C	cooling, control
coll	thermal solar collectors
D	daylight dependency
f	net floor
fl-lw	floor
fl-up	ceiling
gn	generation sub-system
H	heating
H+W	combined heating and domestic hot water
n	nominal
nd	need
O	occupancy density
p	peak
rg	control sub-system
ru	heat recovery ventilation system
sky	sky
W	domestic hot water
w	window
wl	wall

Acronyms

BH	Single-Boiler for Heating
BW	Single-Boiler for Domestic Hot Water
C	Cooling
CB	Combined Boiler for Heating and Domestic Hot Water
Ch	Chiller
COM	Cost-Optimisation Methodology
CTI	Italian Thermotechnical Committee
DHW, W	Domestic Hot Water
EEM	Energy Efficiency Measure
EEO	Energy Efficiency Option
EPBD	Energy Performance of Buildings Directive
F	Fixed Louvres
GHG	Greenhouse Gas
H	Heating
h	Hourly (h)
KPI	Key Performance Indicator
L	Artificial Lighting
LCA	Life Cycle Assessment
M	Mobile Louvres
M	Monthly (h)
NA	National Annex
NZEB	Nearly Zero-Energy Building
OS	Original State
R	Room Control
RB	Reference Building
RC	Resistive Capacitive
V	Mechanical Ventilation
Z	Zone Control
ZC	Zone and Climatic Control

national minimum energy performance requirements adopt the quasi-steady-state methods (Corrado et al., 2015).

1.2. Quasi-steady-state versus dynamic calculation methods in cost-optimisation procedures

The simplicity of the assessment, as well as the reproducibility of results (van Dijk et al., 2005), made the quasi-steady-state methods to be widely applied over the years, especially for annual evaluations. However, the use of these simplified methods for individual month evaluations may lead to large errors. These errors may be significant in specific cases, e.g., when heating needs dominate and cooling demand is very low, then even small inaccuracies can determine large differences in the cooling needs (Michalak, 2014). During the last decades, many works focused on assessing the accuracy of monthly quasi-steady-state methods when compared to detailed dynamic methods. Generally, noticeable deviations were highlighted between the calculation models. Ballarini et al. (2018) showed that the simplified method presents several issues in assessing the thermal energy needs in intermediate months (i.e., spring and autumn), and overestimates the heating need in winter. Similarly, Kokogiannakis et al. (2008) underlined a general trend of the EN ISO 13970 monthly method (European Committee for Standardization (CEN), 2008) of overestimation with respect to dynamic methods, resulting in different energy ratings for different buildings. Furthermore, the ability of the model in predicting the cooling energy needs was often proven to be not sufficiently accurate. For example, Bruno et al. (2019) demonstrated the consistent overestimation of the thermal energy need for space cooling when compared to the TRNSYS dynamic method. Similar results were also achieved in Bruno et al. (2017b,a) for buildings in the Mediterranean area, and in Michalak (2014) for Northern-East Europe. Several works, such as Wauman et al. (2013) and Kim et al. (2013), point to the utilisation factor as the main source of uncertainty in quasi-steady-state methods. For this reason, different works, such as Corrado et al. (2016) and Beccali et al. (2001), suggest that a dynamic simplified method would be preferable to a quasi-steady-state one. In this context, the lumped-capacitance model of EN ISO 13790 (European Committee for Standardization (CEN), 2008) demonstrated to assess with an acceptable degree of accuracy the space heating and cooling energy needs of buildings, but it seemed to be inadequate to determine the hourly cooling load and peak load in summer (Vivian et al., 2017).

In the last years, the accuracy of quasi-steady-state methods for the definition of cost-optimal levels, compared to dynamic methods, was assessed in a few studies. Corrado et al. (2015) applied the comparative methodology framework through the quasi-steady-state method on two office buildings (representative of the Italian building stock) and then analysed the cost-optimal solutions with the detailed dynamic method of EnergyPlus. Because of the significant deviations detected in terms of both energy demands and energy costs, the Authors concluded that the application of the comparative methodology through dynamic methods is essential to establish whether the quasi-steady-state method defines the cost-optimal solutions with acceptable accuracy. This further analysis was performed by Corrado et al. in Corrado et al. (2019) for a residential building, representative of the Italian building stock. Specifically, the Authors compared the results of the cost-optimisation analysis applied with the monthly quasi-steady-state method and the detailed dynamic model of EnergyPlus. The results highlighted that the choice of the optimisation method is crucial in defining the cost-optimal solutions, suggesting that Member States should accurately consider adopting detailed dynamic calculation methods to identify the national minimum energy performance requirements.

1.3. Aim of the research

The necessity to correctly evaluate the summer thermal behaviour of buildings, ahead of a significant increase in the energy needs for space cooling due to climate change, is forecasting the employment of simplified dynamic models. In fact, the replacement of the currently employed quasi-steady-state methods with the simplified dynamic ones for legislative verifications is currently under discussion in Italy (Corrado et al., 2020). Moreover, the application of the benchmarking method in the Italian national context was firstly developed in 2014 and then reviewed in 2018 (Corrado et al., 2018), based on simplified energy assessment procedures. To comply with the EPBD recast, periodic reviews of the minimum energy performance requirements are demanded at regular intervals, not exceeding five years.

The present work is aimed at investigating the feasibility of applying a simplified dynamic method in the comparative methodology framework for the determination of the minimum energy performance requirements, in comparison with the quasi-steady-state procedure. This research compares the cost-optimal levels, in terms of global cost and package of energy efficiency measures, determined through the simplified dynamic and quasi-steady-state methods for Italy. In addition, this work focuses on whether a more accurate calculation of the thermal energy needs for space heating and cooling leads to a consistent variation in the results of a cost-optimisation procedure.

This research is part of a wider analysis carried out in collaboration with the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), aimed at improving the current Italian cost-optimisation procedure. The Italian comparative methodology was applied to 26 reference buildings (RBs), characterised by different climatic zones, building use categories, periods of construction, and building sizes. In the cost-optimisation procedure 16 different energy efficiency measures were considered. Specifically, an optimisation algorithm, described by Corrado et al. (2014) and based upon the procedures developed by Christensen et al. (2006), was applied to the RBs firstly with the Italian UNI/TS 11300–1 monthly method (Italian Organisation for Stardardisation (UNI), 2014), and then with EN ISO 52016-1 simplified hourly method (European Committee for Standardization (CEN), 2017a). The results of these procedures were then compared in terms of the optimal package of energy efficiency measures and minimum global cost over 30 years of the building economic lifecycle. A sensitivity analysis was carried out on a reference building to highlight the economic parameters that most influence the determination of the global cost.

The article is structured as follows: Section 2 provides a description of the comparative methodology framework, as well as the comparison between the cost-optimal levels defined with the two calculation methods considered; Section 3 presents the selected reference buildings and the energy efficiency measures considered in the optimisation; Section 4 deals with the results and the discussion of the main findings.

2. Methods

In this section, the cost-optimisation procedure is briefly presented, explaining the tool and the main calculation procedures used. The two deployed calculation procedures of the building thermal energy needs for heating and cooling are highlighted, as well as the consistency options applied to harmonise the input parameters and to make the results comparable. Finally, the four main phases of the workflow are presented, as well as the sensitivity analysis procedure.

2.1. Comparative methodology framework

The comparative methodology framework applied in the present work starts with the definition of a set of RBs, representative of the Italian building stock. According to the EPBD recast (European Commission, 2010), the RBs may be either real or archetype buildings, should cover both new and existing residential and non-residential buildings, and should represent the national building stock according to specific criteria, namely climatic conditions, building use, age, and size and shape. The RBs identified for the Italian context and analysed in the present work are presented in Section 3.1. Then, the workflow presented in Fig. 1 is applied to each reference building. This consists of the following steps:

1. Several energy efficiency measures (EEMs) including intervention on both the building envelope and the technical building systems are defined. Each EEM is then provided with different discrete energy efficiency options (EEOs) that represent, for instance, different levels of thermal insulation of the envelope or different efficiency values of the heat generators. A matrix to identify possible technical incompatibilities between EEMs is defined as well,
2. A package of EEMs (and related EEOs) is defined as the starting point of the cost-optimisation procedure, and the related global cost is calculated, as specified in the EN 15459-1 (European Committee for Standardization (CEN), 2017b) technical standard, and
3. The cost-optimisation algorithm, which is thoroughly described in Section 2.1.1, is applied to identify the cost-optimal level of energy performance and the related optimal package of EEMs.

2.1.1. Cost-optimisation algorithm

The proposed cost-optimisation algorithm is an iterative calculation that starts with the definition of N different energy efficiency measure scenarios (i.e., EEMs and related EEOs) applicable to the analysed RB starting from the set of reference EEMs. Then, each ith identified scenario is applied to the reference building, to calculate the building's final and primary energy demands, and the global cost. Among all the tested configurations, the new sub-optimal solution is the one with the largest reduction in global cost. This one is then compared in terms of net present value (NPV) with the previous sub-optimal solution,

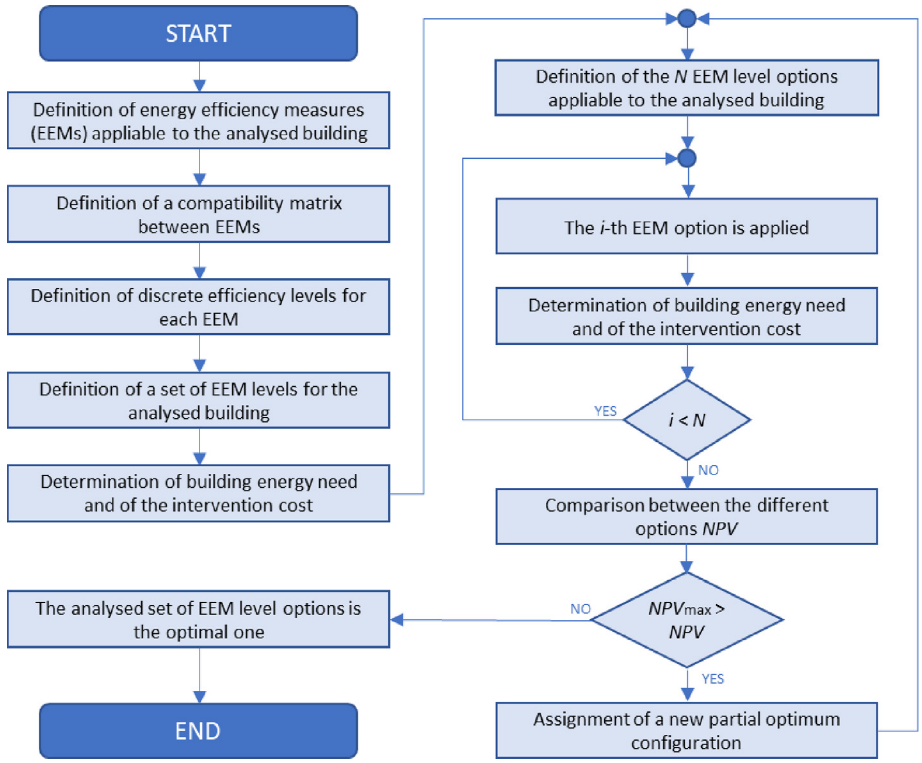

Fig. 1. Flowchart of the cost-optimisation procedure for a reference building.

i.e., the one obtained from the previous iteration. If the current sub-optimal solution *NPV* is higher than the previous sub-optimal solution *NPV*, then the current EEMs and EEOs configuration becomes the new partial optimum configuration, and the iteration starts again. Instead, if the current sub-optimal solution *NPV* is lower than the previous sub-optimal solution *NPV*, the iteration stops, and the previous partial optimum configuration is defined as the optimal solution.

For this specific purpose, an optimisation algorithm developed in MS Excel calculation sheets was implemented. The tool is composed of several sheets for calculating the energy performance related to the building components and technical building systems – according to UNI/TS 11300-1, -2, -3, -4, and -5 (Italian Organisation for Stardardisation (UNI), 2014, 2019, 2010, 2016a,b) and EN ISO 52016-1 (European Committee for Standardization (CEN), 2017a) – and the global cost – according to EN 15459-1 (European Committee for Standardization (CEN), 2017b). An auxiliary sheet is used to associate the input data required to describe the building and carry out the energy calculations with both the quasi-steady-state (Italian Organisation for Stardardisation (UNI), 2014) and the simplified dynamic procedure (European Committee for Standardization (CEN), 2017a) for each package of interventions identified by the optimisation procedure.

2.1.2. Thermal energy needs calculation procedures

The energy needs for heating and cooling for each RB are calculated by applying two different calculation methods, namely the quasi-steady-state monthly method, described in the UNI/TS 11300-1 (Italian Organisation for Stardardisation (UNI), 2014) technical specification (Italian Annex of the EN ISO 13790 (European Committee for Standardization (CEN), 2008)), and the simplified dynamic method, described in the EN ISO 52016-1 (European Committee for Standardization (CEN), 2017a) technical standard. The two calculation procedures differ in many aspects, including the calculation time step, the temporal variation of the boundary conditions, and the modelling of the building components. Indeed, in the monthly method procedure, the effect of the whole building's thermal mass, and thus the dynamic effects, is accounted only in the determination of correction factors for monthly thermal energy needs for heating and cooling. In the EN ISO 52016-1 dynamic model (European Committee for Standardization (CEN), 2017a), instead, the building components (opaque and transparent) are described individually by means of a resistive-capacitive (RC) system, and the respective thermal properties are specified according to the actual mass distribution. The main differences between methods are presented in Table 1.

The final and primary energy demands (thus taking into account the technical building systems) are calculated from the thermal energy needs for space heating and cooling (determined with both the quasi-steady-state and the simplified dynamic method), and applying the simplified procedures presented in the UNI/TS 11300-2, -3, -4, and -5 (Italian Organisation for Stardardisation (UNI), 2019, 2010, 2016a,b) technical specifications.

2.2. Comparison between cost-optimal levels: quasi-steady-state and hourly calculation method

The comparative methodology framework presented in Section 2.1 was applied deploying both the quasi-steady-state and the simplified dynamic procedure. A set of consistency options was applied to both models to make their results comparable. The consistency options applied in the present work are described in Section 3.3. The results of the comparative methodology are then compared in terms of variations in the optimal combinations, in the optimal global costs, and in the heating and cooling thermal energy needs resulting from the application of the two methods. The causes of discrepancies and their implications are investigated as well.

Table 1
Main differences between the deployed methods.

	UNI/TS 11300-1	EN ISO 52016-1
Time step	Month	Hour
Boundary conditions variability	Monthly	Hourly (monthly for ground temperature)
Dynamic effects	Gain utilisation factor for heating/ Heat transfer utilisation factor for cooling	Directly accounted in the model
Heat storage in building components	Time constant of the building zone affecting the dynamic effects	Discretisation of building components with a RC model.
Solar and internal heat gains	Purely convective	Separation between radiative and convective

Table 2
Case studies relevant geometric properties.

Building code	Use	Floor area (m^2)	Gross volume (m^3)	Envelope area (m^2)	Compactness ratio (m^{-1})
RMF_N0_E/B	Residential	98	371	368	0.99
RMF_E1_E/B	Residential	162	583	435	0.75
RMF_E2_E/B	Residential	199	725	519	0.72
RPC_N0_E/B	Residential	450	1728	1032	0.60
RPC_E1_E/B	Residential	827	3076	1576	0.51
RPC_E2_E/B	Residential	1088	4136	1994	0.48
RGC_N0_E/B	Residential	1788	6662	2836	0.43
RGC_E1_E/B	Residential	1552	5949	2740	0.46
RGC_E2_E/B	Residential	3506	12685	4721	0.37
UFF_N0_E/B	Office	1519	6100	2129	0.35
UFF_E1_E/B	Office	363	1339	805	0.60
UFF_E2_E/B	Office	2007	7200	2340	0.33
SCU_E1_E/B	School	8935	47223	11538	0.24

2.3. Sensitivity analysis

A sensitivity analysis was applied to a case study in order to evaluate the influence of the main economic parameters considered in the calculation procedure. The economic parameters were grouped into four main categories: the cost related to the envelope energy efficiency measures, the cost related to the technical building systems energy efficiency measures, the cost of the energy carriers, and the interest rate. Each of these was considered one at a time, with both a percentage increase and a percentage decrease in cost. The cost-optimisation procedure was applied deploying the simplified dynamic calculation procedure for the assessment of the energy needs for heating and cooling, as presented in Section 2.2. The results were analysed in terms of global cost variation calculated as the difference from the reference global cost (the one determined from the cost-optimisation procedure applied to the building in the original state), divided by the reference global cost.

3. Application

In this section, the two first phases of the deployed method, which are prior to the calculation procedures, are explained. At first the group of buildings chosen for the calculation, according to the European Framework, is presented, then the 16 EEMs analysed in the procedure are outlined.

3.1. Representative buildings

Representative buildings reflect the most common geometrical characteristics, thermal properties of the building envelope, and technical building system typologies, representing the average situation in a market segment. The benefits of the reference building approach consist of the translation of the results to the entire building stock and the consequent reduction in the number of simulations. Enhancing the number and building use categories of RBs, assessed in the cost-optimisation procedure, leads to representative results but increases the complexity of the application and the computational efforts. This contribution is part of Ministerial work based on the updating of the Italian comparative methodology framework of the cost-optimal energy performance levels, complying with the Guidelines to the European Regulation (European Commission, 2012b) also in the selection approach of the selected RBs. A trade-off between the legislative constraints and the set of RBs that realistically describe the representativeness of the Italian building stock was followed.

For this application, RBs located in two Italian climatic zones (i.e., Milan located in zone E, and Palermo in zone B with respectively 2404 and 751 heating degree days), for five building types (i.e., single-family house, multi-family house, apartment block, office, and educational building) constructed in three different periods were defined. The main geometric characteristics of each reference building are reported in Table 2.

The residential buildings in climatic zone E are based on the TABULA project (Anon, 2015), while typologies defined by ENEA (Margiotta and Puglisi, 2009) were used for office buildings. The classification of technical building systems was based on data from the CRESME survey (Baldazzi et al., 2013) according to the type of generation system, the emission subsystem, and the heat control system for heating systems, while the type of technical system and the heat control system were used to define the cooling systems.

The building identifier codes are composed as follows: the first three characters represent the building type, i.e., single-family house (RMF), multi-family house (RPC), apartment block (RGC), offices (UFF), and educational building (SCU), the following two characters represent the period of construction, i.e., between 1946–1976 (E1),1977–1990 (E2), and new (N0), and the last character represents the climate zone of the building location, i.e., Milan (E) or Palermo (B).

Moreover, in Table 3 the major thermophysical characteristics in the current state of the existing RBs are summarised. Specifically, the mean thermal transmittance of the opaque and transparent building envelope components, the building energy services, and the thermal generator sub-system of the assessed objects are presented. Table 3 does not report the main thermophysical properties of new RBs since they are influenced by the initial package of energy efficiency measures analysed.

Table 3
Energy performance related features of the RBs.

Building code	Thermal transmittance				Energy services					Heat generators[b]
	U_{wl} (W m^{-2} K^{-1})	U_{fl-up} (W m^{-2} K^{-1})	U_{fl-lw} (W m^{-2} K^{-1})	U_w (W m^{-2} K^{-1})	H[a]	C[a]	W[a]	V[a]	L[a]	
RMF_E1_E	1.48	2.16	2.00	4.90	x	x	x			CB, Ch
RMF_E1_B	1.18	2.16	2.00	4.90	x	x	x			CB, Ch
RMF_E2_E	0.76	1.14	0.98	2.80	x	x	x			CB, Ch
RMF_E2_B	1.10	2.16	1.30	4.90	x	x	x			CB, Ch
RPC_E1_E	1.15	1.65	1.30	4.90	x	x	x			BH, BW, Ch
RPC_E1_B	0.90	1.65	1.30	4.90	x	x	x			BH, BW, Ch
RPC_E2_E	0.81	0.97	1.14	3.70	x	x	x			BH, BW, Ch
RPC_E2_B	0.98	1.65	1.60	3.80	x	x	x			BH, BW, Ch
RGC_E1_E	1.15	1.65	1.30	4.90	x	x	x			BH, BW, Ch
RGC_E1_B	0.90	1.65	1.30	4.90	x	x	x			BH, BW, Ch
RGC_E2_E	0.76	0.97	0.98	3.70	x	x	x			BH, BW, Ch
RGC_E2_B	0.98	1.65	1.30	4.90	x	x	x			BH, BW, Ch
UFF_E1_E	1.53	1.20	0.87	2.60	x	x	x	x	x	BH, BW, Ch
UFF_E1_B	1.53	1.20	1.30	4.00	x	x	x	x	x	BH, BW, Ch
UFF_E2_E	0.50	0.85	0.87	3.20	x	x	x	x	x	BH, BW, Ch
UFF_E2_B	0.50	0.85	1.30	4.90	x	x	x	x	x	BH, BW, Ch
SCU_E1_E	1.41	1.65	0.68	4.25	x		x	x	x	BH, BW
SCU_E1_B	1.41	1.65	0.68	4.25	x		x	x	x	BH, BW

[a]Building energy services considered: space heating (H), space cooling (C), domestic hot water (W), mechanical ventilation (V), and artificial lighting (L).
[b]CB = Combined boiler for space heating and domestic hot water, Ch = chiller, BH = single-boiler for space heating, BW = single-boiler for domestic hot water.

Table 4
Overview of the considered energy efficiency measures.

Code	Description	Relevant parameters
EEM1	External wall thermal insulation	U_{wl} (W m^{-2} K^{-1})
EEM2	Cavity wall thermal insulation	U_{wl} (W m^{-2} K^{-1})
EEM3	Ceiling thermal insulation	U_{fl-up} (W m^{-2} K^{-1})
EEM4	Floor thermal insulation	U_{fl-lw} (W m^{-2} K^{-1})
EEM5	Windows refurbishment	U_w (W m^{-2} K^{-1})
EEM6	Solar shading devices	Fixed or mobile louvres
EEM7	Chiller	*EER* (–)
EEM8	Heat generator for space heating	*COP* (–)
EEM9	Heat generator for domestic hot water	$\eta_{W,gn}$ (–)
EEM10	Combined heat generator for space heating and domestic hot water	$\eta_{H+W,gn}$ (–)
EEM11	Heat pump for space heating, domestic hot water, and space cooling	*COP* (–), *EER* (–)
EEM12	Thermal solar system	A_{coll} (m^2)
EEM13	Photovoltaic system	W_p (kW)
EEM14	Heat recovery ventilation system	η_{ru} (–)
EEM15	Space heating control sub-system	$\eta_{H,rg}$ (–)
EEM16	Lighting system	P_n/A_f (W m^{-2}) F_O (–) F_C (F_D) (–)

3.2. Energy efficiency measures

The sixteen EEMs considered in the comparative methodology include interventions on the opaque and the transparent building envelope, on the space heating, space cooling, domestic hot water (DHW), ventilation, and lighting systems, and the renewable energy systems (i.e., thermal solar and photovoltaic). For each EEM, up to five different energy efficiency options (from EEO1 to EEO5) with an increasing level of efficiency were considered. The number of EEOs tested is variable depending on the RB.

Each energy efficiency measure considered in the present work is provided in Table 4. Specifically, each EEM is identified through an identification code (from EEM1 to EEM16), a relevant describing parameter, and the total number of EEOs considered. In Fig. 2 the compatibilities between EEMs are presented.

The EEMs related to the opaque building envelope consist of the thermal insulation of the external walls with external or in-cavity insulation (respectively EEM1 and EEM2), and the upper and lower floors (respectively EEM3 and EEM4) with external insulation. The EEMs related to the transparent envelope, instead, consist of the installation (or replacement in existing buildings) of high-performance windows (EEM5) and solar shading systems (EEM6). For the existing buildings, EEO1 represents the current state, EEO3 and EEO4 are characterised by the thermal transmittance complying with the Italian minimum energy performance requirements (reference building) in force respectively in 2015 and 2021 (Italian Republic, 2015), EEO2 represents a 20% increase of EEO3's thermal transmittance, and EEO5 is a better-performing solution. For new buildings, instead, EEO2 represents the reference building in 2015, EEO1 its 20% increase, EEO3 is the reference building in 2021, and EEO4 is a better-performing solution.

The EEMs related to the technical building systems consist of the replacement or installation of high-efficiency generators for space heating, space cooling, domestic hot water production, and mechanical ventilation (with heat recovery), and of high-efficiency control systems. The efficiency of the control system is specified in the Italian standards (Italian Organisation for Stardardisation (UNI), 2019, 2010) to account for the control accuracy, as defined in EN 15500-1 (European Committee for Standardization (CEN), 2017c). The control accuracy allows calculating the additional energy needs for heating or cooling caused by the inaccuracy of the zone temperature control. Following the Italian standard procedure (Italian Organisation for Stardardisation (UNI), 2019, 2010), this variation in the energy needs is considered as a reduction of the whole heating or cooling system

	EEM1	EEM2	EEM3	EEM4	EEM5	EEM6	EEM7	EEM8	EEM9	EEM10	EEM11	EEM12	EEM13	EEM14	EEM15	EEM16
EEM1																
EEM2	X															
EEM3	✓	✓														
EEM4	✓	✓	✓													
EEM5	✓	✓	✓	✓												
EEM6	✓	✓	✓	✓	✓											
EEM7	✓	✓	✓	✓	✓	✓										
EEM8	✓	✓	✓	✓	✓	✓	✓									
EEM9	✓	✓	✓	✓	✓	✓	✓	✓								
EEM10	✓	✓	✓	✓	✓	✓	✓	X	X							
EEM11	✓	✓	✓	✓	✓	✓	X	X	X	X						
EEM12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					
EEM13	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
EEM14	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
EEM15	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
EEM16	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

✓ Compatible EEMs
X Incompatible EEMs

Fig. 2. Compatibility matrix between EEMs.

efficiency. The control efficiency is a number between zero and one, with the lowest value corresponding to manual control and the highest one to a proportional band room control. Downstream of technical and economic feasibility studies, traditional low-temperature boilers, condensing boilers, and air-to-water heat pumps were considered for space heating (EEM8), DHW production (EEM9), and combined heating and DWH production (EEM10). Multi-split systems were instead considered for space cooling (EEM7). For offices and schools, EEMs related to the lighting system were considered as well, namely LED systems with or without automatic control (EEM16).

The EEMs related to renewable energy systems consist of the installation of solar collectors for domestic hot water production (EEM12), and photovoltaic panels (EEM13). The EEOs considered for EEM12 represent different domestic hot water coverage needs. For EEM13, instead, the EEOs were defined by considering the minimum PV peak power required by the Italian Legislative Decree 28/2011 (Italian Republic, 2011) (EEO2), its variation by 20% - lower (EEO1) and higher (EEO3) - and its increase by 40% (EEO4) and 60% (EEO5). In Appendix, from Table A.1 to Table A.6, the EEOs values are presented for each EEM and case study.

The investment costs of the considered EEMs were derived from market analysis and pricelist, they were considered inclusive of VAT, transport, labour, and installation costs (UNICMI Economic Studies Office, 2018; Anon, 2017a,b). The costs of the energy carriers (electricity and natural gas) were instead supplied by the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) (Italian Regulatory Authority for Energy, 2018).

3.3. Consistency options

Due to the difference in time-steps between the two calculation methods, some options described below were implemented to ensure consistency between the input data. Some of the improvements proposed in the Italian National Annex (NA) to EN ISO 52016-1 (Italian Thermotechnical Committee CTI, 2021) were implemented as well.

(a) Climatic data. The Italian Thermotechnical Committee (CTI) typical meteorological year (Italian Thermotechnical Committee CTI, 2016), was used in this procedure. To have all the climatic data for the timestamp, the solar irradiance values provided by CTI, which are defined as a mean of the measured data obtained in a one-hour timestep, were interpolated to obtain values in the middle of the hour of interest. For instance, the original CTI data referred to 9 a.m. is the mean of the values measured between 8 a.m. and 9 a.m., hence, this value refers, as a timestamp, to 8:30 a.m. The corrected value, used in this procedure, is a linear interpolation between original data and refers, as timestamp, to 9 a.m. A second correction of the data present in the model year concerned the hours of sunrise and sunset, with the modification and correction of any values that were not compatible with the actual progression of the irradiance values. Depending on the calculation method used, either hourly values or monthly averages were applied.

(b) Internal heat sources. The values of the internal heat gains were determined according to the monthly calculation method (UNI/TS 11300-1 (Italian Organisation for Stardardisation (UNI), 2014)). In the hourly method, a standard daily profile of the internal heat gains was defined on an hourly basis following the occupancy schedule provided by EN 16798-1 (European Committee for Standardization (CEN), 2019) and constructed in such a way that the monthly average values are consistent with the monthly procedure.

(c) Ventilation airflow rates. The values were determined according to the monthly calculation method (UNI/TS 11300-1 (Italian Organisation for Stardardisation (UNI), 2014)); in the hourly method, a standard daily profile of the ventilation flow rate was defined on an hourly basis following the occupancy profile, constructed in such a way as to keep the average monthly values consistent with the monthly procedure.

(d) Correction coefficient of the total solar factor of glazing (F_w). The value of the total solar factor at normal incidence was corrected as specified in the Italian NA of EN ISO 52016-1 (Italian Thermotechnical Committee CTI, 2021) in accordance with the work of Karlsson and Roos (2000), taking into account both the angle of incidence of solar radiation and the properties of the glass.

(e) Temperature of the sky vault (θ_{sky}). It was determined following the procedure of the Italian NA of EN ISO 52016-1 (Italian Thermotechnical Committee CTI, 2021) according to the formulation of Aubinet (1994), who expressed the sky temperature as a function of the external partial vapour pressure. The same model was deployed in UNI/TS 11300-1 (Italian Organisation for Stardardisation (UNI), 2014).

3.4. Modelling options for economic analysis

The calculation of the actualised global cost was performed in compliance with the EN 15459 technical standard (European Committee for Standardization (CEN), 2017b) specifications, as follows:

- the financial perspective was assumed,
- initial investment costs, energy costs, maintenance costs, replacement costs, and residual value were considered (Corrado et al., 2018),
- a thirty-year calculation period was adopted (European Commission, 2012a),
- the lifespan of the technical building system components was assumed varying from 15 to 35 years depending on the technology,
- an interest rate of 4% was considered,
- a variable increase rate for the energy costs was adopted over the calculation period (Corrado et al., 2018),
- annual maintenance costs were assumed varying from 0% to 4% of the investment cost, depending on the technology,
- maintenance and replacement costs of the existing windows and heating and domestic hot water generators were considered.

3.5. Sensitivity analysis

The sensitivity analysis was applied to the single-family house built between 1977–1990 in Milan (RMF_E2_E) with a lower floor adjacent to a non-conditioned space and a pitched roof adjoining the outside environment. For each of the cost categories, a percentage cost increase and decrease was determined. This latter was set to 10% for the cost related to the envelope EEMs, the technical building systems EEMs, and the energy carriers. The interest rate was instead set to ± 1% as an absolute percentage variation.

4. Results and discussions

4.1. Cost-optimal solutions

The results presented in this article are part of a wider study. An overview of the main differences derived from the use of a simplified dynamic procedure is provided, focusing on the optimal combination, global cost, and the energy needs for heating and cooling in the current state. As this article is addressed at performing the comparisons on the overall results of the analysed building cluster, the outcomes of the procedure application on single buildings are not provided. At first analysis, it seems evident that the variations, both in terms of global cost and optimal combination, between the optimisations related to the monthly calculation method UNI/TS 11300-1 (Italian Organisation for Stardardisation (UNI), 2014) and those related to the hourly method of EN ISO 52016-1 (European Committee for Standardization (CEN), 2017a) are moderate. In Table 5 the EEM option for each analysed building for both the monthly, the number on the left, and hourly calculation procedure, the number on the right, are presented. A colour indication highlights the differences; the more the colour is intense, the greater the difference is in the results. Fig. 3 shows the number of energy efficiency measures in the cost-optimal packages that are different between the two calculation methods. It is immediately evident that most of the variations are related to the EEM4 measure, i.e., the measure referring to the reduction of heat transmission through the floor. The variations result in a reduction of the efficiency level between the monthly and the hourly case. The reasons for this are twofold; firstly, some of the buildings concerned by this measure are adjacent to the ground, and exchanges with the ground are considered differently in the two calculation procedures. Indeed, in the monthly procedure corrective coefficients are applied, while in the hourly method the procedure described in EN ISO 13370 (European Committee for Standardization (CEN), 2017d) is followed. Secondly, the interventions on the exterior surface of the lower floor are extremely economical, therefore even with minimal variations in the results of the energy performance, due to the different calculation methods, and with the consequent reduction in energy costs, this measure is extremely cost-effective. The variations are higher, in some cases moving from the maximum to the minimum level of the EEOs, in the buildings with the floor on ground and in some of the cases located in Palermo, since, given the lower energy requirements, even small variations are more significant in percentage terms.

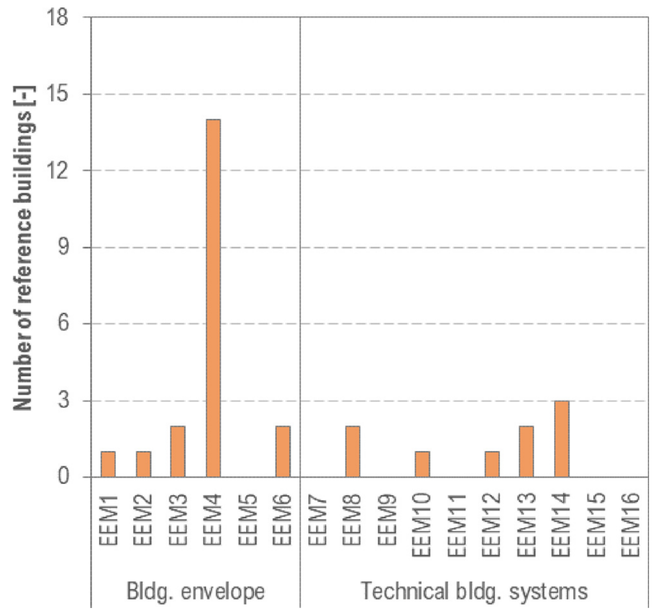

Fig. 3. Number of reference buildings in which the EEOs differ in hourly and monthly cost-optimal configurations.

Despite the calculation time steps for the performance determination of the technical building systems are the same in the two calculation procedures, the different energy need obtained

Table 5
EEMs optimal packages for the monthly (number on the left) and hourly (number on the right) calculation procedures.

Building code	EEM1	EEM2	EEM3	EEM4	EEM5	EEM6	EEM7	EEM8	EEM9	EEM10	EEM11	EEM12	EEM13	EEM14	EEM15	EEM16
RMF_N0_E	3/3	-*	5/5	5/5	1/1	2/2	1/1	1/1	1/1	0/0**	0/0	1/1	1/1	2/3	3/3	-
RMF_N0_B	1/1	-	5/5	5/5	3/3	2/2	1/1	1/1	1/1	0/0	0/0	1/1	3/3	2/2	3/3	-
RMF_E1_E	3/3	-	2/2	5/1	2/2	1/1	1/1	0/0	0/0	3/3	0/0	1/1	4/4	-	4/4	-
RMF_E1_B	1/1	-	2/2	1/1	3/3	2/3	1/1	0/0	0/0	3/3	0/0	1/1	2/3	-	4/4	-
RMF_E2_E	0/0	2/2	2/2	4/4	1/1	1/1	1/1	0/0	0/0	3/3	0/0	1/1	4/4	-	4/4	-
RMF_E2_B	0/0	1/1	2/2	5/1	1/1	2/3	1/1	0/0	0/0	3/3	0/0	1/1	2/4	-	4/4	-
RPC_N0_E	3/3	-	5/5	5/4	1/1	2/2	1/1	2/2	1/1	0/0	-	1/1	3/3	1/1	3/3	-
RPC_N0_B	1/1	-	5/5	5/4	3/3	2/2	1/1	2/2	1/1	0/0	-	1/1	3/3	1/1	3/3	-
RPC_E1_E	0/0	2/2	5/5	5/4	1/1	3/3	1/1	3/3	2/2	0/0	-	1/1	4/4	-	4/4	-
RPC_E1_B	1/1	-	5/5	5/1	1/1	3/3	1/1	3/3	2/2	0/0	-	3/3	4/4	-	4/4	-
RPC_E2_E	1/1	-	5/5	4/4	1/1	1/1	1/1	3/3	2/2	0/0	-	3/3	4/4	-	4/4	-
RPC_E2_B	0/0	2/1	5/5	4/4	1/1	3/3	1/1	1/3	1/1	0/0	-	3/3	4/4	-	4/4	-
RGC_N0_E	4/3	-	5/5	5/4	1/1	2/2	1/1	2/2	1/1	0/0	-	1/1	3/3	3/3	3/3	-
RGC_N0_B	1/1	-	5/5	5/5	3/3	2/2	1/1	2/2	1/1	0/0	-	1/1	3/3	1/1	3/3	-
RGC_E1_E	0/0	2/2	5/5	5/4	2/2	3/3	1/1	2/3	2/2	0/0	-	2/2	4/4	-	4/4	-
RGC_E1_B	1/1	-	5/5	5/1	3/3	3/3	1/1	3/3	1/1	0/0	-	2/2	4/4	-	1/1	-
RGC_E2_E	0/0	2/2	5/5	4/4	1/1	3/3	1/1	0/0	0/0	2/2	-	2/3	4/4	-	4/4	-
RGC_E2_B	0/0	1/1	5/5	5/1	1/1	3/3	1/1	0/0	0/0	2/2	-	3/3	4/4	-	4/4	-
UFF_N0_E	2/2	-	2/2	3/2	5/5	2/2	0/0	-	-	0/0	2/2	1/1	3/3	1/1	3/3	2/2
UFF_N0_B	1/1	-	2/3	2/1	1/1	2/2	0/0	-	-	0/0	2/2	1/1	3/3	1/1	3/3	2/2
UFF_E1_E	0/0	2/2	2/2	1/1	1/1	3/3	1/1	0/0	0/0	2/2	0/0	1/1	4/4	1/2	4/4	3/3
UFF_E1_B	0/0	1/1	1/1	1/1	1/1	3/3	1/1	0/0	0/0	2/2	0/0	1/1	4/4	1/1	4/4	3/3
UFF_E2_E	0/0	2/2	2/2	1/1	1/1	3/3	1/1	0/0	0/0	1/2	0/0	1/1	4/4	2/2	4/4	3/3
UFF_E2_B	0/0	1/1	1/1	1/1	1/1	3/3	1/1	0/0	0/0	2/2	0/0	1/1	4/4	1/2	4/4	3/3
SCU_E1_E	0/0	2/2	5/5	3/4	1/1	1/1	-	0/0	0/0	1/1	-	1/1	4/4	4/4	4/4	2/2
SCU_E1_B	0/0	1/1	4/5	1/4	1/1	1/1	-	0/0	0/0	2/2	-	1/1	4/4	1/1	4/4	2/2

* - = EEM not applicable
** 0/0 = EEM not applied

* - = EEM not applicable.
** 0/0 = EEM not applied.

with the quasi-steady-state and the simplified dynamic procedure can modify the energy efficiency measure cost-effectiveness. For this reason, the measures concerning the heat generator for space heating (EEM8) and the combined heat generator for space heating and domestic hot water (EEM10) suffered variations in some cases.

The measures referred to the refurbishment of the windows (EEM5), the variation of the chiller (EEM7) and the DHW generator (EEM9) use/efficiency, the installation of a heat pump for heating, cooling, and DHW production (EEM11), the replacement of the space heating control sub-system (EEM15), and the variation of the electric lighting system properties (EEM16) have no deviation in the results. Therefore, at least in the considered case studies, the influence of a different calculation method for the determination of the thermal energy needs for heating and cooling on the cost-optimal measures revealed to be negligible.

The global cost per different cost categories (normalised over the conditioned floor area) of the cost-optimal levels between hourly and monthly calculation methods is represented in Fig. 4. The global cost is given by the sum between the energy, the investment, and the maintenance costs. The difference in terms of global cost is negligible in almost all cases, with values generally within ±6%. This minimal deviation between the two investigated methods is due to the introduction of consistency options to make the monthly and hourly calculations comparable, which leads to similar energy demand and consequently similar energy cost. While for the residential cases, there is not a specific trend in the global cost deviation, the cost-optimal solution of the office buildings presents a global cost reduction consequent to the use of the hourly method due to specific technical building systems and user characteristics of such type of buildings that are more sensitive to the calculation method properties.

Significant variations in the investment and maintenance costs can be attributed to different levels of EEOs, between the simplified dynamic and quasi-steady-state methods, concerning the technical building's systems. However, in some cases, different EEOs on the technical building system (i.e., from EEM7 to EEM16) are compensated by different EEOs on the building envelope (i.e., from EEM1 to EEM6). Therefore, for this reason, a general trend cannot be outlined. For instance, the RB RPC_E2_B presents the most percentage decrease in the investment cost (about 50%) between the monthly cost-optimal level compared to the hourly one. In that case, the monthly cost-optimal level favours the economical options to insulate the opaque building envelope (i.e., cavity wall thermal insulation, EEM2) but does not encourage the installation of a high-efficiency generator for space heating (i.e., EEM8), as foreseen from the hourly cost-optimal level.

The energy cost, on the other hand, is strongly dependent on the thermal energy need calculation and the energy carrier typology consumed. For example, in UFF_E1_E the installation of a unit of heat recovery on the mechanical ventilation system, accompanied by differentiation in the energy performance assessment methodology, allows to save about 30% of the energy cost in the hourly configuration.

The analysis of the variations of the thermal energy needs between the two calculation methods, shown in Fig. 5, was carried out considering all the existing buildings in the current condition, before the application of the cost-optimisation procedure. The trend shows a slight increase in the heating energy needs and a reduction in the cooling energy needs when passing from the monthly method to the hourly one. This deviation is mainly related to the correction factor F_w and the calculation of the temperature of the sky vault. In fact, it is possible to notice for both locations an average reduction of the F_w factor and an increase in the temperature difference between the external environment and the sky. These changes correspond respectively to a reduction of the solar gains and to an increase of the radiative heat transfer with the sky, variations which are therefore compatible with the differences in outcomes.

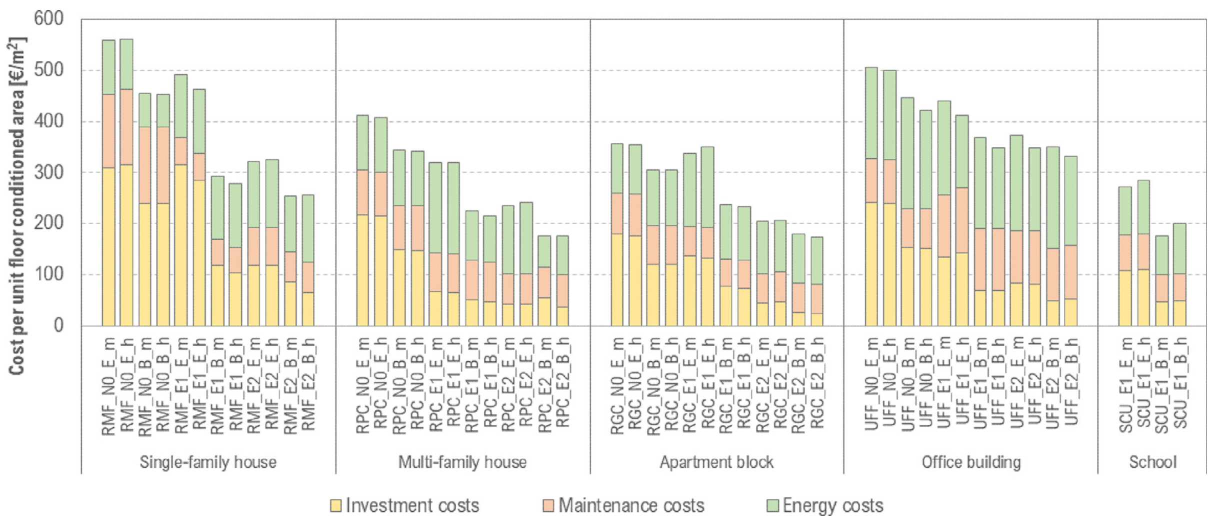

Fig. 4. Global cost per different cost categories in cost-optimal results between monthly (m) and hourly (h) calculation methods.

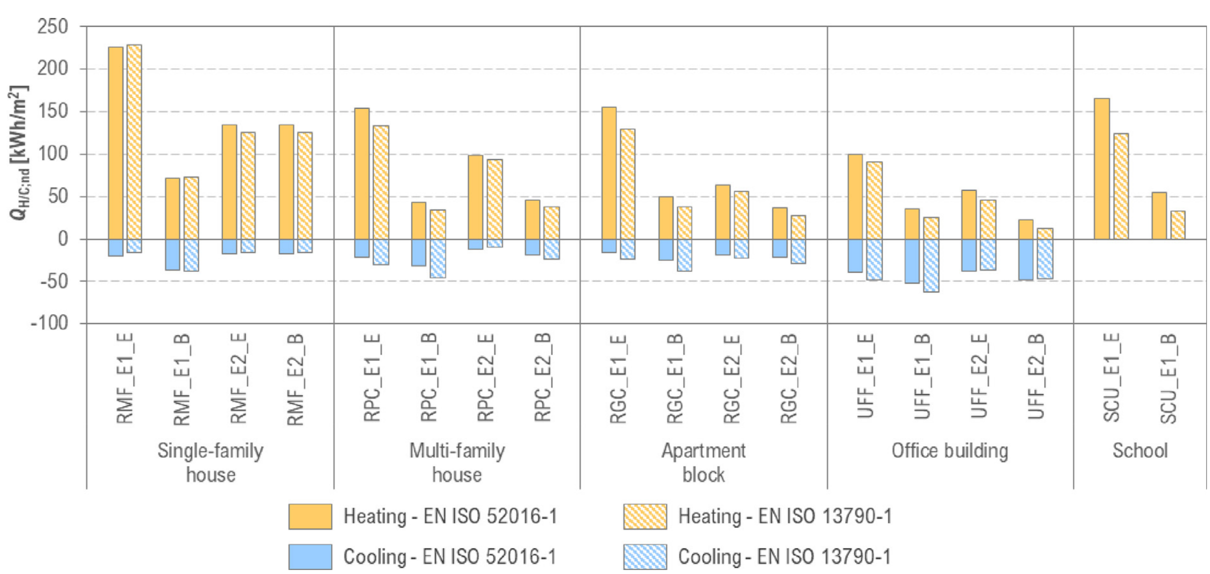

Fig. 5. Heating and cooling thermal energy needs ($Q_{H/C,nd}$) for the reference buildings.

4.2. Sensitivity analysis

The results of the sensitivity analysis, presented in Table 6, show a very limited variation in the EEM levels from the reference cost-optimal result. In particular, the change in the cost-optimal solution occurs only for three optimisations and concerns the same energy efficiency measures: the upper (EEM3) and lower (EEM4) horizontal envelope insulation. In all three cases, the change is minimal, with only an EEO level increase.

Due to the specificity of the analysed building, the amount of heat transfer associated with the surfaces of the roof and cellar floor on the total value of the building envelope is close to 50%. Therefore, from an economic point of view, the aforementioned energy efficiency measures are the most suitable compared to the other envelope upgrading solutions.

For this reason, in the case of a decrease of −10% on the costs related to the envelope, it is more economical to invest in higher levels of thermal insulation that also provide higher benefits. This consideration is also applicable to the other two scenarios that change the cost-optimal solution since the increase in the cost of energy and the reduction of the interest cost determine an increase of the general costs with the need for a shift to the most cost-effective EEMs.

The overall global cost trend is in line with the cost variations: a decrease as the cost of the parameter decreases and an increase as the cost of the parameter increases. This general trend is also visible in the optimal cost reports of the EU countries (European Commission, 2018b). What determines, in absolute value, the greatest change is the scenario in which the real interest rate has changed, as this index will discount the cash flows of all cost categories, i.e., investment costs, maintenance costs, replacement

Table 6
Sensitivity analysis results on building RMF_E2_E.

Analysed parameter	Variation	Number of modified EEM levels	Global cost (€/m²)	Global cost variation (%)
Envelope EEM (EEM1 ÷ EEM6)	−10%	2	316	−3.1
	+10%	0	335	2.6
Technical building systems EEM (EEM7 ÷ EEM16)	−10%	0	321	−1.5
	+10%	0	331	1.5
Cost of energy carriers (natural gas, electricity)	−10%	0	313	−4.1
	+10%	2	338	3.7
Interest rate	−1%	2	353	8.3
	+1%	0	302	−7.4

costs, and the cost of energy carriers. On the contrary, what determines in absolute value a lower percentage change is the change in the unit prices related to the technical building systems.

4.3. Future developments of cost-optimisation procedure

The cost-optimisation methodology (COM) is a single-objective procedure, intending to periodically update the national minimum energy performance requirements, based on the mere minimisation of the global cost through the energy efficiency package of measures variation. The COM is divided into financial and macroeconomic procedures. The former focuses on the economic evaluation of private investment, while the latter considers the cost of emitting climate-changing gases into the atmosphere. The introduction of minimum energy performance requirements is a basic condition to minimise the energy and environmental footprint of the building stock. However, targeting the decarbonisation 2050 goals (European Commission, 2019), the high-energy efficient building plays a crucial role in greenhouse gas (GHG) reduction, but the health, the different domains of environmental comfort (thermal, acoustic, lighting, and indoor air quality), and productivity of the occupants should be considered in the EU legislative framework (Kephalopoulos et al., 2017).

Although the macroeconomic approach of the COM takes into consideration the CO_2 emission cost, a multi-domain-based approach is required since the idea to push social and environmental benefits through global cost minimisation is no longer supportable (Boermans et al., 2011). In this regard, it is of foremost importance that the cost-optimal level coincides with the efficiency measures needed to make a nearly zero-energy building (NZEB). The next-generation COM should take into consideration more key performance indicators (KPIs) in the energy, economic, social, and environmental domains (dos Reis and Dias, 2020; Longo et al., 2019) For instance, the payback period, energy consumption, comfort indices (*PMV*, *PPD*, hours of discomfort), levels of indoor pollutants, life cycle assessment (LCA) indices (embodied energy and embodied carbon), and other indicators should be considered (Chastas et al., 2020).

Moreover, recent research activities suggest new elements, applications, and implementations to enhance the cost-optimisation analysis. For instance, Zangheri et al. (2022) suggest the evaluation of district-level procedures, and Fernandez-Luzuriaga et al. (2021) propose the application of the COM to a residential building stock to set out different energy refurbishment scenarios. In this last case, the results are not extended from the reference building to the building stock, but the cost-optimal level is calculated directly for an urban context. Ferrara and Fabrizio (2017), instead, investigate the climate change effect on the COM. They applied different future weather data projections to the cost-optimisation analysis to evaluate the resilience of the energy efficiency measures to an NZEB single-family house located in France. Buildings officially protected for their architectural or historical merit are usually ignored in the cost-optimisation methodology. Ramos et al. (2019) present a COM to renovate a historical building built in the Eighteenth century, preserving the aesthetic appearance of the building.

The presented works show multiple implementations and applications of the COM highlighting that is crucial to shift from a single-objective procedure to a holistic multi-domain approach. Precisely because the EU 2050 (European Commission, 2019) targets imply achievement in the social, environmental, energy as well as economic fields.

5. Conclusions

The analysis of the literature regarding the optimisation procedures, which are usually developed according to the European framework, showed a lack of studies on the influence of different calculation procedures, especially the simplified dynamic ones. This article was aimed to broaden this field of research through the comparison between a quasi-steady-state and a simplified dynamic procedure. In this work, a cost-optimisation procedure was applied to 26 RBs different in climatic zone, building use category, period of construction, and size and shape. Two different procedures for the determination of the thermal energy needs for space heating and cooling were applied; the first one, based upon the monthly calculation procedure of the EN ISO 13790 (European Committee for Standardization (CEN), 2008) standard, and the second one, based on the hourly calculation procedure of the EN ISO 52016-1 (European Committee for Standardization (CEN), 2017a) standard. The comparison was performed by analysing both the differences in global cost and the measures related to the cost-optimal configuration.

Slight differences are shown between the optimal solutions deriving from the application of the two methods, mainly related to the different models of heat transmission through the building envelope components.

The analysis of the overall cost and the combination of EEMs highlighted no major differences. Two main reasons can be deemed for this result, the first one is that the methods were compared on a monthly basis or even over a thirty-year period, such as for the global cost, thus normalising the hourly variations from the hourly procedure; the second one is that only the determination of the thermal energy needs for space heating and cooling differs while the calculation procedures for the technical building systems were the same.

Future works should enhance the technical building system calculation procedures currently contained in the cost-optimisation methodology, in order to adopt hourly approaches allowing the development of a comparative analysis between a full monthly procedure and a full hourly one, or even analyse the effect of other energy and environmental parameters in the analysis. Moreover, a global sensitivity analysis will be performed in future works to assess the interdependency between variables and the influence of parameters.

CRediT authorship contribution statement

Franz Bianco Mauthe Degerfeld: Software, Formal analysis, Writing – original draft, Visualization. **Matteo Piro:** Software, Formal analysis, Writing – original draft. **Giovanna De Luca:** Writing – original draft, Visualization. **Ilaria Ballarini:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Vincenzo Corrado:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vincenzo Corrado reports financial support was provided by ENEA National Agency for New Technologies Energy and Economic Sustainable Development. Vincenzo Corrado reports a relationship with EPB Center that includes: non-financial support.

Data availability

Data will be made available on request

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Appendix

In this section the values for the EEOs for each EEMs of every considered RB are presented.

See Tables A.1–A.6.

Table A.1
EEO values for EEM1-5 in residential buildings in Milan.

	RMF			RPC			RGC			Parameter	EEO				
	N0	E1	E2	N0	E1	E2	N0	E1	E2		1[a]	2	3	4	5
EEM1	x			x			x			U_{wl} (W m^{-2} K^{-1})	1.50	0.36	0.30	0.26	0.17
		x	x		x	x		x	x		OS	0.36	0.30	0.28	0.19
EEM2	x	x		x		x	x			U_{wl} (W m^{-2} K^{-1})	–	–	–	–	–
			x						x		OS	0.27	–	–	–
					x			x			OS	0.37	–	–	–
EEM3	x			x			x			U_{fl-up} (W m^{-2} K^{-1})	1.67	0.43	0.36	0.31	0.26
		x	x								OS	0.32	0.26	0.24	0.20
					x	x		x	x		OS	0.46	0.37	0.34	0.29
EEM4	x			x			x			U_{fl-lw} (W m^{-2} K^{-1})	2.50	0.60	0.50	0.43	0.28
		x									OS	0.84	0.69	0.64	0.42
			x		x			x	x		OS	0.63	0.52	0.48	0.32
						x					OS	0.38	0.31	0.29	0.19
EEM5	x			x			x			U_{w} (W m^{-2} K^{-1})	3.80	2.20	1.80	1.40	1.10
		x	x		x	x		x	x		OS	2.30	1.90	1.40	1.10

[a]OS = Original state.

Table A.2
EEO values for EEM1-5 in residential buildings in Palermo.

	RMF			RPC			RGC			Parameter	EEO				
	N0	E1	E2	N0	E1	E2	N0	E1	E2		1[a]	2	3	4	5
EEM1	x			x			x			U_{wl} (W m^{-2} K^{-1})	1.50	0.54	0.45	0.43	0.28
		x	x		x	x		x	x		OS	0.54	0.45	0.40	0.26
EEM2	x	x		x	x		x	x		U_{wl} (W m^{-2} K^{-1})	–	–	–	–	–
			x								OS	0.37	–	–	–
						x			x		OS	0.35	–	–	–
EEM3	x			x			x			U_{fl-up} (W m^{-2} K^{-1})	1.67	0.66	0.54	0.50	0.40
		x	x								OS	0.41	0.34	0.32	0.26
					x	x		x	x		OS	0.59	0.49	0.46	0.37
EEM4	x			x			x			U_{fl-lw} (W m^{-2} K^{-1})	2.50	0.93	0.77	0.73	0.48
		x									OS	1.29	1.07	0.93	0.62
			x		x			x	x		OS	0.97	0.80	0.70	0.47
						x					OS	0.58	0.48	0.42	0.28
EEM5	x			x			x			U_{w} (W m^{-2} K^{-1})	5.00	3.80	3.20	3.00	1.60
		x	x		x	x		x	x		OS	3.80	3.20	3.00	1.60

[a]OS = Original state.

Table A.3
EEO values for EEM6-16 in residential buildings.

	RMF			RPC			RGC			Parameter	EEO				
	N0	E1	E2	N0	E1	E2	N0	E1	E2		1[a]	2	3	4	5
EEM6	x			x			x			Fixed (F) or mobile (M) louvres	F	M	–	–	–
		x	x		x	x		x	x		OS	F	M	–	–
EEM7	x										3.30	–	–	–	–
		x	x							*EER* (–)	OS	3.30	–	–	–
				x			x				3.00	–	–	–	–
					x	x		x	x		OS	3.00	–	–	–
EEM8	x	x	x								3.70	4.10	–	–	–
				x			x			*COP* (–)	1.00	3.70	4.10	–	–
					x	x					OS	0.94	1.00	3.70	4.10
								x	x		OS	0.95	1.00	3.70	4.10
EEM9	x	x	x	x			x			$\eta_{W,gn}$ (–)	0.93	1.00	–	–	–
					x	x		x	x		OS	0.93	1.00	–	–
EEM10	x			x			x				1.00	–	–	–	–
		x	x							$\eta_{H+W,gn}$ (–)	OS	0.93	1.00	–	–
					x	x		x	x		0.93	1.00	–	–	–
EEM11	x										3.10	4.10	–	–	–
		x	x							*COP* (–)	4.10	–	–	–	–
				x	x	x	x	x	x		–	–	–	–	–
	x										2.90	3.50	–	–	–
		x	x							*EER* (–)	3.50	–	–	–	–
				x	x	x	x	x	x		–	–	–	–	–
EEM12	x										1	2	3	–	–
		x	x								OS	1	2	3	–
				x							7	12	17	–	–
					x	x				A_{coll} (m^2)	OS	7	12	17	–
							x				20	30	50	70	–
								x	x		OS	20	30	50	70
EEM13	x										2.00	2.50	3.00	–	–
		x	x								OS	1.36	1.70	2.04	–
				x							3.20	4.00	4.80	–	–
					x					W_p (kW)	OS	5.60	7.00	8.40	–
						x					OS	6.40	8.00	9.60	–
							x				4.80	6.00	7.20	–	–
								x			OS	7.20	9.00	10.80	–
									x		OS	11.20	14.0	16.80	–
EEM14	x			x			x			η_{ru} (–)	0.60	0.70	0.90	–	–
		x	x		x	x		x	x		–	–	–	–	–
EEM15[b]	x			x			x			$\eta_{H,rg}$ (–)	Z	R	ZC	–	–
		x	x		x	x		x	x		OS	Z	R	ZC	–
EEM16	x	x	x	x	x	x	x	x	x	P_n/A_f (W m^{-2})	–	–	–	–	–
	x	x	x	x	x	x	x	x	x	F_O (–)	–	–	–	–	–
	x	x	x	x	x	x	x	x	x	F_C - F_D (–)	–	–	–	–	–

[a]OS = Original state.
[b]Z = Zone control, R = room control, ZC = zone and climatic control.

Table A.4
EEO values for EEM1-5 in non-residential buildings in Milan.

	UFF			SCU	Parameter	EEO				
	N0	E1	E2	E1		1[a]	2	3	4	5
EEM1	x				U_{wl} (W m^{-2} K^{-1})	1.50	0.36	0.30	0.26	0.17
		x	x	x		OS	0.36	0.30	0.28	0.19
EEM2	x					–	–	–	–	–
		x			U_{wl} (W m^{-2} K^{-1})	OS	0.15	–	–	–
			x			OS	0.18	–	–	–
				x		OS	0.12	–	–	–
EEM3	x					1.50	0.30	0.25	0.22	0.18
		x	x		U_{fl-up} (W m^{-2} K^{-1})	OS	0.32	0.26	0.24	0.20
				x		OS	0.46	0.37	0.34	0.29
EEM4	x					1.88	0.45	0.38	0.33	0.21
		x	x		U_{fl-lw} (W m^{-2} K^{-1})	OS	0.84	0.69	0.64	0.42
				x		OS	0.38	0.31	0.29	0.19
EEM5	x				U_w (W m^{-2} K^{-1})	5.00	2.20	1.80	1.40	1.10
		x	x	x		OS	2.30	1.90	1.40	1.10

[a]OS = Original state.

Table A.5
EEO values for EEM1-5 in non-residential buildings in Palermo.

	UFF			SCU	Parameter	EEO				
	N0	E1	E2	E1		1[a]	2	3	4	5
EEM1	x				U_{wl} (W m^{-2} K^{-1})	1.50	0.54	0.45	0.43	0.28
		x	x	x		OS	0.54	0.45	0.40	0.26
EEM2	x				U_{wl} (W m^{-2} K^{-1})	–	–	–	–	–
		x				OS	0.15	–	–	–
			x			OS	0.18	–	–	–
				x		OS	0.12	–	–	–
EEM3	x				U_{fl-up} (W m^{-2} K^{-1})	1.50	0.46	0.38	0.35	0.28
		x	x			OS	0.41	0.34	0.32	0.26
				x		OS	0.59	0.49	0.46	0.37
EEM4	x				U_{fl-lw} (W m^{-2} K^{-1})	1.88	0.70	0.58	0.55	0.36
		x	x			OS	1.29	1.07	0.93	0.62
				x		OS	0.58	0.48	0.42	0.28
EEM5	x				U_{w} (W m^{-2} K^{-1})	5.00	3.80	3.20	3.00	1.60
		x	x	x		OS	3.80	3.20	3.00	1.60

[a]OS = Original state.

Table A.6
EEO values for EEM6-16 in non-residential buildings.

	UFF			SCU	Parameter	EEO				
	N0	E1	E2	E1		1[a]	2	3	4	5
EEM6	x				Fixed (F) or mobile (M) louvres	F	M	–	–	–
		x	x	x		OS	F	M	–	–
EEM7	x				*EER* (–)	3.30	–	–	–	–
		x	x			OS	3.30	–	–	–
				x		–	–	–	–	–
EEM8	x				*COP* (–)	–	–	–	–	–
		x	x	x		OS	–	–	–	–
EEM9	x				*COP* (–)	–	–	–	–	–
		x	x	x		OS	–	–	–	–
EEM10	x				$\eta_{H+W,gn}$ (–)	0.93	1.05	–	–	–
		x	x			0.93	1.03	–	–	–
				x		0.93	1.00	3.10	4.20	–
EEM11	x				*COP* (–)	3.00	3.50	–	–	–
		x	x			3.10	4.20	–	–	–
				x		–	–	–	–	–
	x				*EER* (–)	2.80	3.20	–	–	–
		x	x			2.90	3.10	–	–	–
				x		–	–	–	–	–
EEM12	x				A_{coll} (m^2)	2	4	6	8	10
		x				OS	1	2	3	4
			x	x		OS	2	4	6	8
EEM13	x				W_p (kW)	8.8	11.0	13.2	–	–
		x				OS	3.8	4.8	5.8	–
			x			OS	8.8	11.0	13.2	–
				x		OS	52.8	66.0	79.2	–
EEM14	x				η_{ru} (–)	0.6	0.7	0.9	–	–
		x	x	x		OS	0.6	0.7	0.9	–
EEM15[b]	x				$\eta_{H,rg}$ (–)	Z	R	ZC	–	–
		x	x	x		OS	Z	R	ZC	–
EEM16	x				P_n/A_f (W m^{-2})	6	6	–	–	–
		x	x			OS	6	6	–	–
				x		OS	6	–	–	–
	x				F_O (–)	1.0	0.8	–	–	–
		x	x			OS	1.0	0.8	–	–
				x		OS	1.0	–	–	–
	x				F_C - F_D (–)	1.0	0.9	–	–	–
		x	x			OS	1.0	0.9	–	–
				x		OS	1.0	–	–	–

[a]OS = Original state.
[b]Z = Zone control, R = room control, ZC = zone and climatic control.

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