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Energy-optimized vs. cost optimized design of high-performing dwellings: the case of multi-family buildings

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Abstract

Living in multi-family buildings is very common in Italy and it is important to optimize the design strategies to minimize the energy demand of these buildings and their related operational costs. This is particularly important for low-income tenants, and is pursued by many social housing developments where a good energy performance design is reached. In this work, a simulation-based optimization methodology that combines the use of TRNSYS® with GenOpt® is applied in order to minimize two objective functions - the annual primary energy demand and the operational energy cost - in different system technology scenarios, and verify the differences between energy-optimized design and cost-optimized design in a northern Italy climate. The study is performed on a typical floor of a real multi-family building for social housing. The envelope optimization demonstrates a potential reduction of the energy demand and cost for heating and cooling of more than 35%. The relationship between optimal solutions, system technology scenarios and optimization objectives is deeply analyzed. It is possible to find a set design solutions that are optimal in all the analyzed scenarios. This provides a set of design alternatives that are close to the environmental optimum and are able to reduce the low-income tenants vulnerability.

Keywords: simulation-based optimization; multi-family building; social housing; energy system technology scenarios, operational cost

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1. Introduction

In Italy, according to the most recent census (ISTAT 2010), 54.9% of Italian families live in apartments in multi-family buildings. Furthermore, 78% of families that cannot afford buying a place live in rented apartments. Therefore, multi-family buildings represent a significant part of the building stocks and will be the major typology for new developments in cities, where 85.5% of people live in apartments.

Besides, since multi-family is the common building typology for social housing interventions, improving their energy performance also constitutes a challenge for contrasting the risk of energy poverty for low-income households (Faiella et al., 2014). A recent study (Copiello, 2016) demonstrates that energy efficiency may help the low-income tenants be neutral about the rent increase that may occur for new social housing interventions. Moreover, after the introduction of the Directive 2012/27/EU and the principles of heat accounting, many problems related to the cost repartition and the non-homogeneity between the different apartments in multi-family buildings have arisen (Ficco et al., 2016; Fabrizio et al., 2017)).

These are the reasons why increasing the energy efficiency and improving the design quality of new and existing multi-family buildings for social housing may significantly reduce the energy consumptions and the CO2 emissions of the residential sector while keeping the energy operational costs for tenants under control.

1.1. The optimization tools and objectives in the literature

In the context of more and more ambitious performance requirement for buildings, fostered by European regulation, the building design has become a complex optimization problem. New tools and methods that combine building energy simulation with optimization techniques have been developed and studied, enabling designers to accurately calculate the actual energy consumption of buildings in different design configurations.

In the literature, such studies adopt either quasi steady-state energy assessment models compliant to EN ISO 13790 (Kapsalaki et al, 2012; Ferreira et al., 2016) or dynamic simulation models (Wang et al. 2011; Bayraktar et al, 2012) when the selection and comparison of design alternatives is either manual or automated. However, the development of building dynamic simulation and its combination with automated optimization has been recognized as a powerful tool for designers to evaluate thousands of different building design solutions (Xing et al., 2016). This allows the building design to be accurately optimized according to different objective functions, which entails the dynamic calculation of the building energy consumption as a starting point.

Depending on the aim of the study, the choice of the optimization objective can vary between primary energy minimization, global cost or life cycle cost minimization, thermal or visual comfort maximization, etc., but it is important to consider that this choice clearly affects the resulting building design. Also, the techno-economic scenario in which the building is optimized is affected by uncertainty and it is necessary to consider multiple scenarios in order to find robust solutions (Rysanek et al, 2013).

Many researchers are dealing with the problem of developing strategies for the economic feasibility of energy-optimal building design, as there is often a gap between the economic optimum and the zero (or positive) energy target (Ferrara et al., 2014; Pikas et al, 2015; Zacà et al, 2015). Energy and cost are indeed the two objectives that are most frequently addressed in the literature. 34% of studies related to the building design optimization problems (Evins, 2013) deal with the energy objective, while cost objectives are addressed in around 30% of the studies. Among those addressing cost optimization, only 20% focus on operational costs. In fact, the majority of such studies add up investment, maintenance, replacement and operational costs occurring within the building lifecycle in the so-called global cost objective function. This is because the European Directive 2010/31/EU has introduced the cost-optimal methodology as a tool for defining the energy performance level leading to the lowest global cost within the building economic lifecycle.

The cost-optimal methodology is often adopted in a context where the building owner is also the building user. In this situation, the building owner can optimize his investments and operational costs in order to minimize the global cost over a defined time period. In this perspective, the operational cost may often be hidden within the value of the global cost. This is the case of most of the studies dealing with the cost-optimal methodology application (Kurnitski et al. 2011, Tronchin et al. 2012, Tronchin et al., 2014, Pikas et al., 2017).

When dealing with social housing, however, the building owner, who is also the investor, is different from the building user. In this context, different financial models may be applied and special attention has to be given to the operational costs, as the low-income tenants directly pay for them.

1.2. The optimization variables in the literature

The design space in which the building has to be optimized depends on the considered design variables. These variables may be related to the building envelope, not only in terms of construction, but also in terms of geometry and facade design, or to the energy system, in terms of technology and design, or both. For example, some authors (Prando et. al., 2015; Brandao de Vasconcelosa et al., 2016) considered only variables related to the building envelope, such as window type, insulation thickness and shading type. Other authors (Ascione et al. 2016, Monetti et al. 2015) compared different technologies for heating and cooling energy supply.

Some of the building design optimization studies considered both envelope and energy systems, assuming that these two groups of design variables are strictly interrelated. This was proven for a single-family building (Ferrara et. al, 2016a), where it was demonstrated that the choice of the building system influences the optimal design of the building envelope variables. However, very few studies investigated this problem in relation to the more complex multi-family buildings design.

1.3. Aim of the present work

This work presents a replicable simulation-based optimization methodology to study in deep the multi-family building design optimization problem in the Italian context.

The envelope-related design variables affecting the building heating and cooling energy needs are identified and optimized in different heating and cooling systems scenarios, addressing separately the non-renewable primary energy demand and the operational cost minimization objectives. The study defines an economic objective function exclusively based on the operational cost for heating and cooling as relevant for the social housing model, where low-income tenants are more interested in low energy operational cost.

A theoretical framework for properly weighting the heating and cooling energy needs according to the different objectives and system scenarios is presented, aiming at exploring the dependence of the optimal design solution on such objectives and scenarios.

It is expected that reducing energy needs also reduces the operational costs, however, due to differences in the weighting terms related to the energy or cost objectives, the energy-optimized and the cost-optimized building design may not be the same. In fact, the resulted optimal solutions are investigated in order to understand how and to what extent the two optimal design configurations differ one from the other. The energy optimum, which minimizes the primary energy demand and CO_2 emissions of the multi-family building, is compared to the economic optimum that will be preferable in the tenants' perspective.

Further considerations about the influence of the energy supply system scenario in the determination of such optimal solutions will be provided together with a study on the resilience of the design variables to the variation of the optimization objectives and/or the system scenario.

The analysis is based on a case-study that is representative of new construction for social housing in Italy and the findings of the study could inform the current design practice.

2. Simulation-based methodology

2.1. The optimization process

The methodology that is proposed involves the coupling between a dynamic energy simulator and an optimizer in a simulation-based optimization process. Among the available tools for simulation-based optimization, the presented methodology relies on TRNSYS® as simulation tool and GenOpt® as optimization tool, as shown in Figure 1.

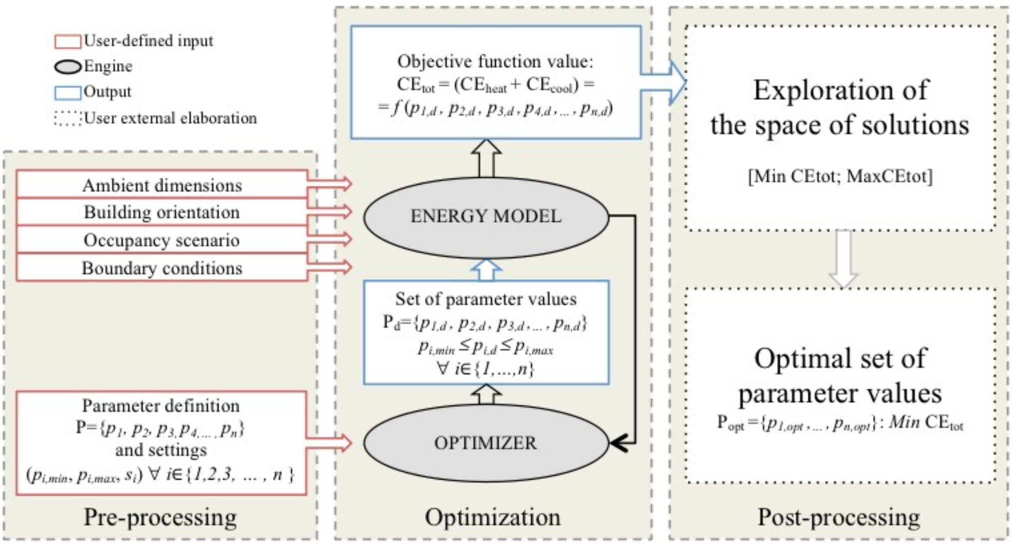

Figure 1. Simulation-based optimization methodology for the present study

In the pre-processing stage, the TRNSYS model is created including the building boundary conditions, and the set of design parameters is defined.

In the optimization stage, the iterative process driven by a PSO optimization algorithm leads to evaluate a great number of design solutions, each related to a different set of parameter values, until the objective function is minimized. The PSO is chosen for its ability to deal with discrete variables in building design problems (Ferrara, 2017a). The output of the optimization stage is a big dataset containing, for each solution that was evaluated within the process, the objective function value, the parameter values that are related to each objective function and other secondary functions related to that set of parameter values. The post-processing includes the exploration of the space of solutions contained in that dataset and of the optimal set of parameter values that is associated to the minimized objective function.

2.2. Statement of the optimization problem

As mentioned above, the purpose of this study is to compare the energy optimization against the operational energy costs optimization of the design of a multi-family building.

The set of possible design options is the n-dimensional design space that is defined by the **P** set of *n* user-defined parameters p, where $p_{i,d}$ denotes a value assumed by the parameter p_i in a potential design solution *d*. Each parameter p represents a design variable that is able, by varying, to affect the objective function of the optimization.

The values assumed by such parameters may vary in a discrete space according to the number of steps $s_{i,max}$, numbered with consecutive integers from 0 to $s_{i,max}$, in which the space between the lower and upper bounds $p_{i,min}$ and $p_{i,max}$ of each parameter variation range is divided. Based on this, $p_{i,d}$ denotes the value assumed by the parameter p_i corresponding to the step number $s_{i,d}$.

In this context, the optimization problem that is addressed in this study can be stated as follows

Find $\quad p_{i,d}\ \forall \mathrm{i} \in \{1,2,3,\dots,\mathrm{n}\}$ $\quad$ such that $\qquad$ (1.1)

minimize $\quad \mathrm{OF} = \mathrm{Q_h}(\mathbf{P}) \cdot \mathrm{w_h}\left(\mathrm{T}_{h,k}\right) + \mathrm{Q_c}(\mathbf{P}) \cdot \mathrm{w_c}\left(\mathrm{T}_{c,j}\right) \qquad \mathrm{k} \in \{1,2,\dots,l\}$

$\mathrm{j} \in \{1,2,\dots,\mathrm{m}\} \qquad$ (1.2)

where $\quad \mathrm{P} = \left\{p_{1,}, p_2, p_3, \dots, p_n\right\} \subset \mathbb{Q}^{\mathrm{n}} \qquad$ (1.3)

subject to $\quad p_{i,min} \le p_{i,d} \le p_{i,max} \qquad \forall \mathrm{i} \in \{1,2,3,\dots,\mathrm{n}\} \qquad$ (1.4)

$$p_{i,d} = p_{i,min} + \frac{s_{i,d}}{s_{i,max}}\left(p_{i,max} - p_{i,min}\right) \qquad s_{i,d} \in \left\{0,1,\dots,s_{i,max}\right\} \qquad (1.5)$$

where $\mathrm{Q_h}$ is the annual energy demand for space heating and $\mathrm{Q_c}$ is the annual demand for space cooling, both evaluated by the dynamic simulation tool; $\mathrm{T}_{h,k}$ and $\mathrm{T}_{c,j}$ are related to the technical system that is used for supplying the heating and the cooling energy, respectively. The terms $\mathrm{w_h}$ and $\mathrm{w_c}$ are the weighting terms of the heating and cooling energy demands that are used for computing the objective function *OF*.

2.3. Definition of the objective functions

For the purpose of this study, two different optimization processes have to be carried out separately, one optimizing the energy performance and the other optimizing the operational energy cost. Therefore, two objective functions have to be defined.

For the energy optimization, the objective function is the annual specific non-renewable primary energy demand for heating and cooling. In this case, the weighting terms in Eq. (1.2) are computed as follows

$$\mathrm{w_{h,energy}} = \frac{f_{T_{h,k}}}{\eta_{T_{h,k}}} \tag{2.1}$$

$$\mathrm{w_{c,energy}} = \frac{f_{T_{c,j}}}{\eta_{T_{c,j}}} \tag{2.2}$$

where $\eta_{T_{h,k}}$ and $\eta_{T_{c,j}}$ are the mean seasonal efficiencies of the energy systems $T_{h,k}$ and $T_{c,j}$ for heating and cooling supply, depending on the adopted energy conversion technology. The terms $f_{T_{h,k}}$ and $f_{T_{c,j}}$ represent the primary energy conversion factors related to the energy carriers that are used by the selected energy systems. It has to be pointed out that such conversion factors usually differ from one European Member State to the others, depending on the characteristics of the national energy production and supply systems.

Therefore, the objective function for energy optimization is defined as follows

$$\mathrm{OF}_{Energy} = \mathrm{Q_h} \cdot \frac{f_{T_{h,k}}}{\eta_{T_{h,k}}} + \mathrm{Q_c} \cdot \frac{f_{T_{c,j}}}{\eta_{T_{c,j}}} \quad [\mathrm{kWh/(m^2\ yr)}] \tag{3}$$

Concerning the cost optimization, the objective function is the specific annual operational costs for space heating and cooling. The weighting terms of Eq. (1.2) are computed as follows

$$\mathrm{w}_{\mathrm{h,cost}} = \frac{c_{T_{h,k}}}{\eta_{T_{h,k}}} \tag{4.1}$$

$$\mathrm{w}_{\mathrm{c,cost}} = \frac{c_{T_{c,j}}}{\eta_{T_{c,j}}} \tag{4.2}$$

where $c_{T_{h,k}}$ and $c_{T_{c,j}}$ are the average annual prices of one kWh for space heating and cooling, depending on the energy carrier used in the technical systems, and $\eta_{T_{h,k}}$ and $\eta_{T_{c,j}}$ are the seasonal efficiencies of the technical systems $T_{h,k}$ and $T_{c,j}$ as in Eq. (2.1-2.2).

Therefore, the objective function for operational energy cost optimization is defined as follows

$$\mathrm{OF}_{Cost} = \mathrm{Q_h} \cdot \frac{c_{T_{h,k}}}{\eta_{T_{h,k}}} + \mathrm{Q_c} \cdot \frac{c_{T_{c,j}}}{\eta_{T_{c,j}}} \qquad [\mathrm{kWh/(m^2\ yr)}] \tag{5}$$

Similarly to the primary energy conversion factors, also the average annual energy prices may vary throughout Europe according to the tariff adopted by the energy suppliers and the different national energy incentives policies.

Assuming that the present study is carried out in the Italian context, as shown above, the weighting terms may vary according to the energy system technologies and the related energy carriers. Therefore, in order to cover all the possible design solutions, the optimization process should be repeated for each combination of energy systems that may be installed in the building that has to be optimized.

After computing the weights for each of the selected systems for heating and cooling ($\mathrm{w_h}$ and $\mathrm{w_c}$ respectively), the ratio $\mathrm{w_c}/\mathrm{w_h}$ indicates the relative weight of the cooling terms to the heating term (for example, a ratio equal to 2 indicates that the cooling energy demand weights two times the heating demand and therefore the minimization of the objective function will be mostly cooling-driven). It has to be noted that some systems for heating supply may not be combined with others for cooling supply. In those cases, the scenario is defined as “not compatible”. The creation of a matrix

(Table 1) helps identify the feasible solutions and therefore the weights to be given to the objective functions to perform the optimization in multiple energy system scenarios.

Table 1. The matrix of weights for the computation of the objective functions.

	$\mathrm{w_{h,1}}$	$\mathrm{w_{h,\dots}}$	$w_{h,l}$
$\mathrm{w_{c,1}}$	$\mathrm{w_{c,1}/w_{h,1}}$	not compatible	$\mathrm{w_{c,1}/w_{h,l}}$
$\mathrm{w_{c,\dots}}$	$\mathrm{w_{c,\dots}/w_{h,1}}$	$\mathrm{w_{c,\dots}/w_{h,\dots}}$	not compatible
$w_{c,m}$	$\mathrm{w_{c,m}/w_{h,1}}$	$w_{c,m}/w_{h,\dots}$	$w_{c,m}/w_{h,l}$

2.4. On the locus of optimal points

Based on previous considerations, the objective function of the above-presented problem is linear, where Q_h and Q_c are the two independent variables, which depend, in turn, on the set of parameter **P**. Therefore, each objective function value is associated to a certain ratio Q_h and Q_c values or, better, to a set of Q_h,Q_c couples, as there may be different Q_h,Q_c couples leading to the same objective function value. For the given objective function value, the relationship between the values of Qh and Qc may be expressed, based on Eq (1.2), as follows

$$\mathrm{Q_h = -\,Q_c \cdot \frac{w_c}{w_h} + \frac{OF}{w_h}} \qquad (6)$$

where OF is the selected objective function value (either cost or energy) and w_h and w_c are the related weights defined in (2.1-2) and (4.1-2). As a consequence, there may be a set of Q_h,Q_c couples leading to the minimum objective function value (OF_{opt}). On a bi-dimensional graph, as in Figure 2, where Q_c is on the x-axis and Q_h is on the y-axis, the locus of points related to OF_{opt} can be seen in the following form

$$\mathrm{y = -mx + q} \qquad (7)$$

where, based on (6), the slope m is expressed by the w_c/w_h ratio, and the intercept q is expressed by the OF_{opt}/w_h ratio.

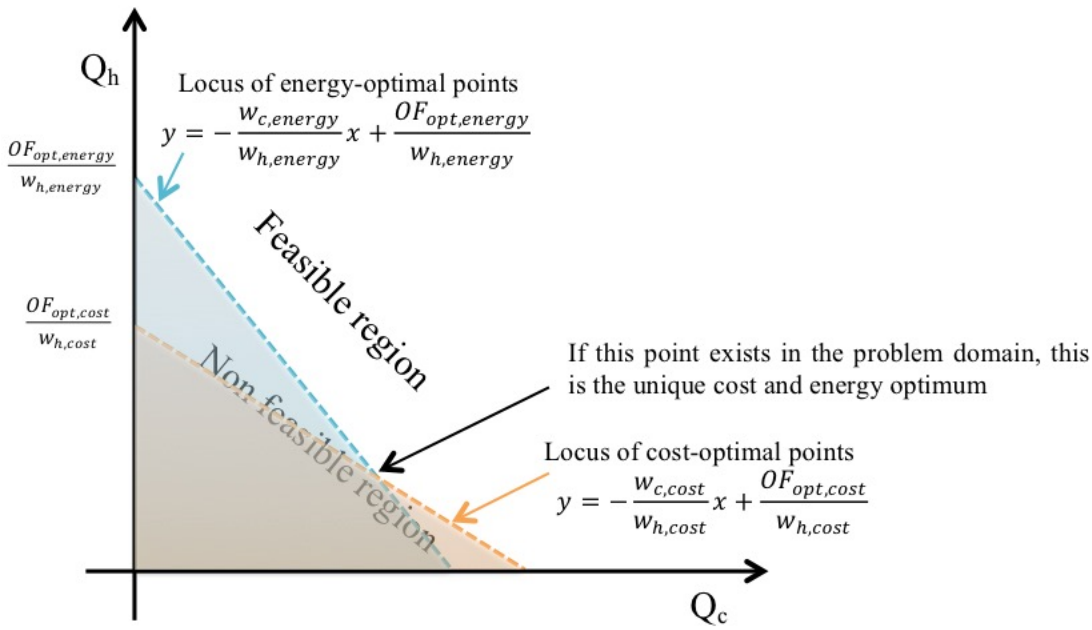

Figure 2. Problem domain and locus of optimal points

The domain of such function depends on the existence of the Q_h,Q_c couples, which depends on the multi-dimensional space of points generated by the all possible sets of parameter **P**. The slope of this line will be different for each system scenario, depending on the matrix of weights in Table 1. The example reported in Figure 2 represents the case in which the ratio $\frac{w_{c,energy}}{w_{h,energy}}$ is greater than the ratio $\frac{w_{c,cost}}{w_{h,cost}}$ but the opposite situation may occur.

For the same system scenario, the locus of cost-optimal points and the one of energy-optimal points may have different slopes, according to their w_c/w_h ratios. In this case, the two lines will cross in a unique point that is both the energy-optimal and cost-optimal solution, if that point is within the problem domain (in other words, if the related Q_h,Q_c couple exists). Otherwise, this is only a theoretical point and the energy-optimum and the cost-optimum will be in different positions on the related lines (see Figure2).

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3. Application to a reference case-study

3.1. Case-study description: initial scenario

The case study is a real multi-family building that is representative of new construction for social housing in Northern Italy (degree days between 2100 and 3000). The whole 6-floors building is composed of 35 apartments of different sizes, for a total net floor area of 2330 m^2.

External walls are made of a layer of bricks (30 cm) with external thermal insulation (10 cm), for a wall thermal transmittance U equal to 0.26 W/(m^2K). The mean thermal transmittance of the transparent surfaces is equal to 1.45 W/(m^2K), which is related to double low-e glass windows with metal frame. The solar factor is 0.59. As shown in Figure3, there are fixed shadings on the facades, including balconies and loggias, which are typical features of Italian construction. Additional details on the case study building features are in (Ferrara et al. 2016b).

For the purpose of this work, one typical floor of the case study building was selected for carrying out optimization studies. As reported in Figure 3, the floor is composed of 7 apartments, having different floor areas and surface-to-volume ratios (Table 2), for a total conditioned floor area of 466 m^2.

Figure 3. Case study building. South façade view, vertical section and plan of the typical 7-apartments floor.

Table 2 reports the specific primary energy consumption and the operational costs related to each apartment and to the entire floor. These values refer to the building actual configuration, which is the so-called "initial scenario" for the optimization.

Table 2. Initial scenario. Annual primary energy consumption and annual energy costs for each apartment and floor values.

		A	B	C	D	E	F	G	Floor
Floor area	(m²)	86.0	48.7	77.5	77.5	47.4	47.6	81.1	465.8
S/V	(m⁻¹)	0.74	0.66	0.26	0.26	0.32	0.27	0.45	0.46
Heating	EP_H (kWh/(m²yr))	26.5	17.7	19.2	18.9	15.5	13.6	26.9	20.7
	C_H (€/m²)	4.27	2.85	3.10	3.04	2.50	2.20	4.34	3.34
Cooling	EP_C (kWh/(m²yr))	15.3	18.3	10.0	9.7	20.7	20.2	14.4	14.7
	C_C (€/m²)	1.26	1.52	0.82	0.80	1.72	1.68	1.18	1.22
DHW	EP_W (kWh/(m²yr))	21.9	25.0	22.4	22.4	25.2	25.1	22.2	23.1
	C_W (€/m²)	1.58	1.80	1.62	1.62	1.82	1.82	1.60	1.66
Vent	EP_V (kWh/(m²yr))	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
	C_V (€/m²)	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Tot	EP_{gl} (kWh/(m²yr))	78.8	76.1	66.7	66.0	76.5	74.2	78.6	73.6
	C_{gl} (€/m²)	8.35	7.41	6.78	6.70	7.28	6.94	8.36	7.46
Energy rating		A1	A1	A1	A1	A1	A1	A1	A1

The primary energy and the costs in such scenario were calculated considering a district heating system for heating supply ($T_{h,ini}$) and electric chillers for cooling supply ($T_{c,ini}$). Therefore the efficiencies, the primary energy factors and the energy costs are defined as follows

- $\eta_{T_{h,ini}}$=0.88, based on the building Energy Performance Certificate;
- $f_{h,ini}$=0.62, as declared by the district heating supplier (the district heating system in that area combines heat generation from waste, from a co-generation plant and from a biomass source);
- $\eta_{T_{c,ini}}$=2.05, Italian reference efficiency for electric chillers (DM 26/06/2015);
- $f_{c,ini}$=1.95, Italian non-renewable primary energy conversion factor for electricity (DM 26/06/2015);

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- $c_{h,ini}$=0.09 €/kWh$_{th}$ (Linea Reti e Impianti, 2016);
- $c_{c,ini}$=0.20 €/kWh$_{el}$ (Eurostat, 2016).

An electric mechanical ventilation system with a heat exchanger is also used, where the mean seasonal efficiency of the sensible heat recovery is 0.5.

The energy simulations for calculating Q_h and Q_c were carried out with the IWEC weather data for Piacenza (weather station 160840, which is the closest to the actual building location).

The primary energy demands for DHW and ventilation were not included in the optimization, as they are not affected by the building envelope design. However, they were calculated with simplified methods in order to estimate the weight of heating and cooling on the total energy demand. The primary energy and cost for DHW were calculated according to the Italian Standard UNI/TS 11300-2 and considering a gas condensing boiler (η_{DHW} =0.85, f_{DHW}=1.05, c_{DHW}=0.08 €/kWh$_{th}$). The primary energy and cost for ventilation (respectively EP_v and C_v) represent the electrical energy use and the related cost for handling of the ventilation air. They are derived considering a 0.5Wh/m^3 specific installed power factor, as indicated for the Italian reference building in DM 26/06/2015, and 0.20 €/kWh$_{el}$ as electricity cost.

As shown in Table 2 the energy rating, according to the current Italian energy performance certification regulation (DM 26/06/2015), is A1 for each apartment and for the entire floor.

3.2. Definition of the optimization parameters and the objective functions

As described in the statement of the optimization problem, the set of design variables and their range and step of variation delineate the design space to be explored within the optimization process. In this study, this process aims at investigating possible performance improvements of a reference multi-family building without changing its layout. Therefore, the optimization parameters were selected among the design variables of the building envelope that may affect the energy needs, while the building geometry and the apartments layout are fixed to their actual configuration.

As shown in Table 3, the selected design variables are related to the thermal resistance of the insulation panels and to the solar absorption coefficient of the external walls, to the type and size of the windows, to the horizontal overhang and fins dimensions of South-oriented windows, to the depth of the loggias facing North and South. The range and the step of their variation were set according to regulation requirements, technical feasibility and market criteria. In the Nomenclature, all the defined parameters are reported.

Table 3. Project parameters description

Parameter Name	Description	unit	min	max	step	Initial value
sISOLN	North walls - thermal resistance insulation	m^2K/W	1.12	5.40	0.53	1.65
sISOLEW	East/West walls - thermal resistance insulation	m^2K/W	1.12	5.40	0.53	1.65
sISOLS	South walls - thermal resistance of insulation	m^2K/W	1.12	5.40	0.53	1.65
abs-back	North walls' absorption factor	-	0.2	0.8	0.3	0.2
abs-backS	South walls' absorption factor	-	0.2	0.8	0.3	0.2
abs-backEW	East/West walls' absorption factor	-	0.2	0.8	0.3	0.2
S_overhproj (m)	Overhang projection length for South windows	m	0.0	1.2	0.2	0.0
Ploggia_S (m)	Overhang projection length for South loggia	m	1.2	3.0	0.3	1.8
Ploggia_N (m)	Overhang projection length for North loggia	m	1.2	3.0	0.3	1.8
WT	North window type	-		1,2,3,4,5,6		1
WTS	South window type	-		1,2,3,4,5,6		1
WTW	West window type	-		1,2,3,4,5,6		1
WTLN	North Loggia window type			1,2,3,4,5,6		1
WTLS	South Loggia window type	-		1,2,3,4,5,6		1
WW_A_Loggia (m)	Window width apt. A Loggia	m	1.1	2.9	0.2	1.3
WW_A_South(m)	Window width apt. A South facade	m	2.1	2.9	0.2	2.5
WW_A_West (m)	Window width apt. A West facade	m	1.1	2.5	0.2	1.7
WW_B_South (m)	Window width apt. B South facade	m	1.5	2.5	0.2	1.9
WW_B_Loggia (m)	Window width apt. B Loggia South	m	1.2	2.6	0.2	1.2
WW_C_South (m)	Window width apt. C South facade	m	1.5	3.3	0.2	1.9
WW_C_North (m)	Window width apt. C North facade	m	1.9	4.3	0.2	2.3
WW_D_South (m)	Window width apt. D South facade	m	1.5	3.3	0.2	1.9
WW_D_North (m)	Window width apt. D North facade	m	1.9	4.3	0.2	2.3
WW_E_South (m)	Window width apt. E South facade	m	1.5	2.5	0.2	1.9
WW_E_Loggia (m)	Window width apt. E Loggia South	m	1.2	2.6	0.2	1.2
WW_F_Loggia (m)	Window width apt. F Loggia South	m	1.4	2.4	0.2	1.8
WW_F_South (m)	Window width apt. F South facade	m	1.3	2.3	0.2	1.3
WW_G_Loggia(m)	Window width apt. G Loggia North	m	2.1	4.9	0.2	3.1
WW_G_North(m)	Window width apt. G North	m	1.2	3.0	0.2	1.2
WW_G_South (m)	Window width apt. G South facade	m	0.9	3.5	0.2	1.1

Table 4 reports the selected options for variation of window type parameters, which are related to different combinations of glass thermal transmittance, solar factor and visible transmittance. The set of parameters, with their dimension and constraints, defines the space of solutions of the problem, in which the search of the optimal design solutions may be conducted with different objectives.

Table 4. Options for window type parameters

ID	Glazing	U_g (W/m^2K)	g (-)	τ_l (-)
1	4/16/4	1.27	0.59	0.71
2	4/15/4	1.10	0.61	0.78
3	6/12/4/12/4	0.70	0.29	0.58
4	6/16/6	1.10	0.33	0.63
5	6/16/6	1.29	0.33	0.66
6	4/16/4/16/4	0.70	0.50	0.64

As mentioned above, different energy system technologies for heating and cooling have been considered in the study, leading to different formulation of the objective functions, based on Equations (3) and (5). Table 5 lists them and shows the main data assumed in the study, as follows:

- η_{gen} represents the reference seasonal energy efficiency for each generation system (DM 26/06/2015);
- $\eta_{T_{h,k}}$ and $\eta_{T_{c,k}}$ represent the seasonal global energy efficiency for the heating and cooling energy systems as the generation efficiency multiplied by a 0.82 standard utilization factor that takes into account the efficiency of the distribution, the emission and the regulation systems;
- $f_{T_{h,k}}$ and $f_{T_{c,k}}$ represent the Italian non-renewable primary energy conversion factors of the specific energy carrier for heating and cooling supply;
- w_{energy} is the energy weight factor as defined in Eq. (2.1) and (2.2);
- $c_{T_{h,k}}$ and $c_{T_{c,k}}$ are the specific costs of the kWh related to the energy carriers of the heating and cooling energy systems;
- w_{cost} is the cost weight factor as defined in Eq. (4.1) and (4.2).

Table 5. Efficiencies and weights related to the technical systems for heating and cooling supply considered in the study.

Heating technology	η_{gen} [-]	$\eta_{T_{h,k}}$ [-]	$f_{T_{h,k}}$ [-]	w_{energy} [-]	$c_{T_{h,k}}$ [€/kWh]	w_{cost} [-]
District Heating (DH)	-	0.88	0.62	0.70	0.09	0.102
Gas Condensing Boiler (GCB)	0.95	0.78	1.05	1.35	0.10	0.128
Gas Heat Pump (GHP)	1.20	0.98	1.05	1.07	0.10	0.102
Electric Heat Pump (EHP)	3	2.46	1.95	0.79	0.20	0.081
Cooling technology	η_{gen} [-]	$\eta_{T_{c,k}}$ [-]	$f_{T_{c,k}}$ [-]	w_{energy} [-]	$c_{T_{c,k}}$ [€/kWh]	w_{cost} [-]
Electric chiller (EC)	2.5	2.025	1.95	0.96	0.20	0.098
Gas Absorption chiller (GAC)	0.6	0.49	1.05	2.13	0.10	0.203

The combination of different energy system technologies for heating and cooling generates the four main scenarios considered in the study, each of them characterized by specific weighting factors to compute the objective functions for the optimization.

3.3. Optimization runs

For each energy system scenario, the optimization process was run both for minimizing and for maximizing the objective functions, so that at the final stage, as post-processing, the space of solution could be explored from its minimum to its maximum.

The GenOpt binary version of the PSO algorithm (Wetter, 2011), based on the performance study reported in (Ferrara, 2017), was run with the following settings: 20 particles, social acceleration set to 2.5, cognitive acceleration set to 1.5, maximum velocity equal to 4. The random seed was set to 1 and the Von Neumann neighborhood topology was used with a size of 5. Each optimization was run until 150 generations are reached.

The four energy system scenarios are defined as follows:

- Scenario 1 corresponds to the initial scenario characterized by a District Heating system for heating supply and an Electric Chiller for cooling supply;
- Scenario 2 is characterized by the combination of a Gas Condensing Boiler for heating supply and an Electric Chiller for cooling supply;
- Scenario 3 is characterized by the combination of a Gas Heat Pump for heating supply and a Gas Absorption Chiller for cooling supply;
- Scenario 4 is characterized by the combination of a Electric Heat Pump for heating supply and an Electric Chiller for cooling supply;

The resulting weights w_c ,$w_h$and the ratio w_c/w_h (in colors) for each scenario are reported, based on the structure of Table 1, for both the energy objective function (Table 6) and the cost objective function (Table 7).

Table 6. The matrix of the total energy weight w_c/w_h of each the design scenario for the computation of the objective functions.

	Heating sys	DH	GCB	GHP	EHP
Cooling sys	w_{energy}	0.70	1.35	1.07	0.79
EC	0.96	1.37	0.71	not feasible	1.22
GAC	2.13	not feasible	not feasible	2.00	not feasible

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Table 7. The matrix of the total cost weight w_c/w_h of each the design scenario for the computation of the objective functions.

	Heating sys	DH	GCB	GHP	EHP
Cooling sys	w_{cost}	0.102	0.128	0.102	0.081
EC	0.098	0.95	0.76	not feasible	1.22
GAC	0.203	not feasible	not feasible	2.00	not feasible

Where, for a specific scenario, the $w_{c,energy}/w_{h,energy}$ ratio equals the $w_{c,cost}/w_{h,cost}$ ratio, the two optimization processes run for minimizing primary energy and cost are expected to lead to equal results. In fact, each optimal solution is characterized by an optimal Q_c/Q_h ratio related to the minimum objective function value. Each different w_c/w_h ratios will lead to different opimal Q_c/Q_h ratios. The difference between the energy and cost optimization for a same system scenario can be explained by the difference between the related energy and cost w_c/w_h ratios. Therefore, it is expected that the greater the difference between w_c/w_h ratios, the biggest differences between the energy-optimized design and the cost-optimized design will be appraised.

4. Results and discussion

Results are presented into three types of diagrams. The first type (e.g. Figure 4) reports on the horizontal axis the energy objective function (3), representing the specific annual non-renewable primary energy need of the case-study floor. The cost objective function (5), representing the specific annual energy cost in euros per square meter of conditioned floor area, is reported on the vertical axis. The second type (e.g. Figure 5) reports the specific energy need for space cooling (Q_c) on the horizontal axis and the specific energy need for space heating (Q_h) on the vertical axis. In these graphs, each point represents one building design configuration associated to one combination of parameter values. The points that were found within the same optimization process, for the same system scenario and objective function, are clustered in clouds where points have the same color (e.g. Figure 8), according to the colors used in Table 6 and Table 7.

The third type of graph (e.g. Figure 10) reports on the vertical axes the range of variation of the parameter values and on the horizontal axis the frequency distribution of those values within the solution in the optimum neighborhoods.

A detailed results analysis is reported for the Scenario 1, then results related to the other scenarios are summarized and compared.

4.1. Scenario 1: detailed analysis of results

Figure 4 reports all points evaluated within the optimization processes in Scenario 1 (DH+EC) with the two objectives. The points of the design space that were evaluated within the energy optimization process are reported in blue, while orange points are referred to the cost optimization process. As shown, these points are part of the same design space, which was searched through in different ways according to the optimization objective. Since the optimization process was run for both minimizing and maximizing the objective functions, the graph shows that the range of possible solutions led to primary energy values within the range 21.6-46.7 kWh/(m^2yr) and to operational energy cost values in the range between 2.7 and 5.8 €/(m^2yr).

The black dot indicates the position of the initial building design in the initial scenario. It is shown that both the primary energy demand for space heating and cooling and the operational energy costs can be reduced by around 40%.

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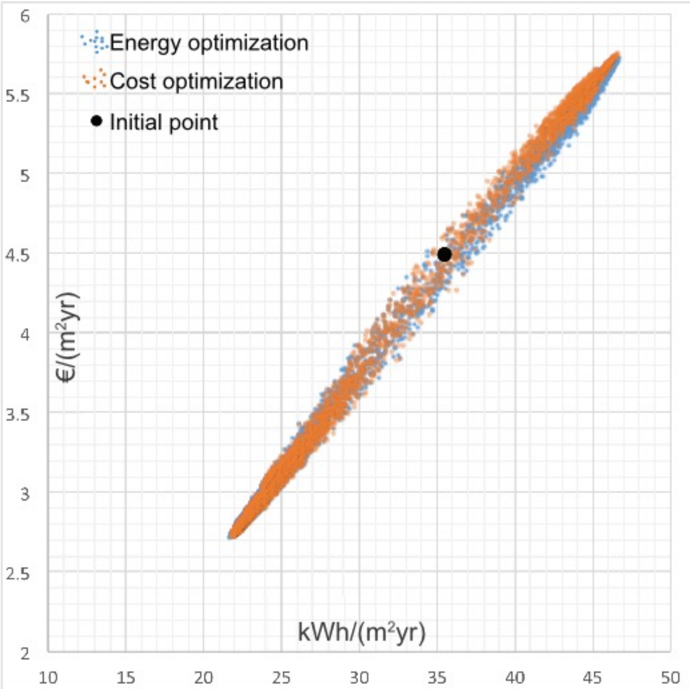

Figure 4. Primary energy (x-axis) and cost (y-axis) values of the points of the design space that were evaluated within the energy optimization (blue) and the cost-optimization (orange) in scenario 1.

It is interesting to note that the two objective functions lead to similar ranges of possible solutions in both dimensions and thus to optimal points that are very close to each other in the graph.

However, looking at Figure 5, it appears that similar objective function values can be reached with many different Qc/Qh couples, therefore related to different building design configurations.

In fact, Figure 5 reports the energy needs for space heating and cooling related to the same points represented in Figure 4. The two *loci* of optimal points are also reported, together with their equations. Based on the theory explained in Section 2.4, a set of points laying on a line that is parallel to the blue or orange line is related to the same primary energy or cost value, respectively. The shape of the clouds reported in Figure 5 demonstrates that there are a great number of design alternatives for each objective function value. In the presented case, this number is higher for energy or cost values in the middle of the solution range, close to the initial configuration (black dot), and becomes smaller when approaching to the *loci* of optimal points.

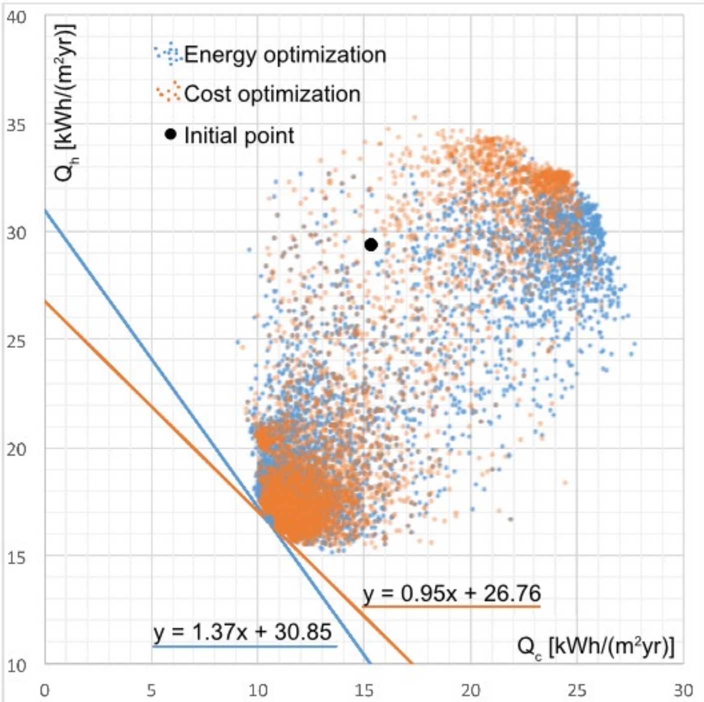

Figure 5. Qc (x-axis) and Qh (y-axis) values of the points of the design space that were evaluated within the energy optimization (blue) and the cost-optimization (orange) in Scenario 1.

However, in the neighborhood of optimum, there is still a significant set of design alternatives leading to similar objective function values, as shown in Figure 6, where a zoom on the optimal region of Figure 5 is reported. The objective function value to be considered as the upper bound of the optimum neighborhood was set to the minimum objective function value increased by 5% of the difference between the minimum and the maximum objective function values (max-min range).

As shown in Figure 6, the optimal points for the two objective functions (the points laying on the respective *loci* of optimal points) are quite close to the crossing point of the two lines, but they do not exactly correspond to that point. This means that there are two different Qc/Qh couples that are related to the two optimal points, each corresponding to a different optimal design configuration.

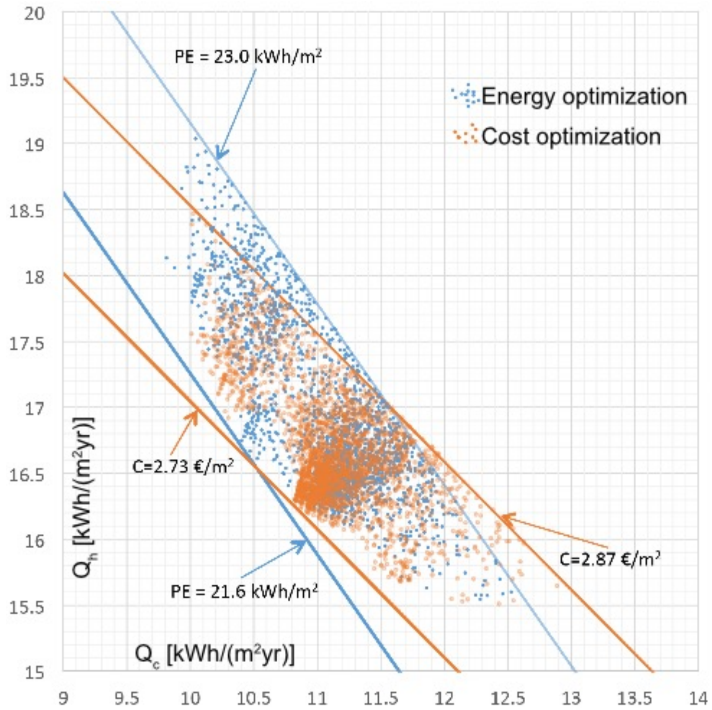

Figure 6. Neighborhood of the optimal points in Scenario 1.

In Table 8, the parameter values related to the energy optimum (the point laying on the blue line in Figure 6; PE=21.6 kWh/m^2) and to the cost optimum (the point laying on the orange line in Figure 6; C=2.73 €/m^2) are reported with the values related to the initial building design configuration.

It is shown that the values of parameters related to external wall insulation in all orientations (sISOLN, sISOLEW, sISOLS) are significantly increased in both optimal scenarios.

The grey color highlights the parameter values where differences occur between the initial solution and the optimal solutions. These differences are related to the external wall solar absorption coefficients, the depth of the loggias and of the external shadings, to the width of some windows and to the window type.

Based on these results, the cost-optimization seems to be heating-driven, coherently with the higher weight related to the heating term. In fact, the higher values of solar absorption coefficients and the smaller depth of loggias increase heating gains in winter. Following the same principle, the window type 6, which is selected for south windows in the cost-optimized scenario, has the same thermal transmittance of the window type 3, but a higher solar factor.

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Table 8. Objective function and parameter values in the initial scenario and in the two optimal solutions (energy and cost). The grey color indicates the parameters of which the optimal value changes according to the objective function.

Parameter name	Initial value (INI)	Energy-optimal value (Eopt)	Cost-optimal value (Copt)	Parameter name	Initial value	Energy-optimal value (Eopt)	Cost-optimal value (Copt)
inWN (m²K/W)	1.73	5.40	5.40	WW_A_Loggia (m)	1.3	1.1	1.1
inWS (m²K/W)	1.73	5.40	5.40	WW_A_South(m)	2.5	2.7	2.1
inWE (m²K/W)	1.73	5.40	5.40	WW_A_West (m)	1.8	1.1	1.1
abs-back (-)	0.2	0.2	0.2	WW_B_South (m)	1.8	1.7	1.5
abs-backS (-)	0.2	0.2	0.5	WW_B_Loggia (m)	1.2	1.6	1.6
abs-backEW (-)	0.2	0.2	0.5	WW_C_South (m)	1.8	1.9	1.7
WT (-)	1	3	3	WW_C_North (m)	2.4	1.9	1.9
WTS (-)	1	3	6	WW_D_South (m)	1.8	1.7	1.7
WTW (-)	1	3	3	WW_D_North (m)	2.4	1.9	1.9
WTLS (-)	1	3	6	WW_E_South (m)	1.8	1.7	1.5
WTLN (-)	1	3	3	WW_E_Loggia (m)	1.2	1.6	1.6
S_overhproj (m)	0	1.2	1.2	WW_F_Loggia (m)	1.8	1.6	1.6
Ploggia_S (m)	1.8	1.8	1.4	WW_F_South (m)	1.2	1.3	1.1
Ploggia_N (m)	1.8	2.1	1.2	WW_G_Loggia(m)	3.1	2.1	2.1
				WW_G_North(m)	1.2	1.1	0.9
				WW_G_South (m)	1.1	1.6	1.6

Point	Qc/Qh ratio	PE kWh/m²	C €/m²
INI	0.51	35.4	4.56
Eopt	0.62	21.6	2.74
Copt	0.67	21.8	2.73

In the last rows of Table 8, the Qc/Qh ratio referred to the initial point (INI), the energy optimum (Eopt) and the cost optimum (Copt) points are reported.

Beyond the resulted absolute objective function values, which may be affected by uncertain modeling assumptions, the most interesting result is related to the wide range of possible building design configuration leading to objective function values in the optimum neighborhood. Within this neighborhood, the variety of design solutions, and thus of different combinations of parameter values, is demonstrated by the range of Qc/Qh ratios. For the system Scenario 1, the Qc/Qh ratio of the points in the optimum neighborhood ranges from 0.53 to 0.8 for the energy optimization and from 0.54 to 0.73 for the cost optimization. These ranges are reported below in Figure 9, together with those related to the other system scenarios.

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4.2. All scenarios: results summary and resilience of the optimum

Figure 7 and Figure 8 report the two representations of the results in all scenarios.

The variations of the max-min ranges of objective function values related to the system scenarios are shown in Figure 7. It is clear that the scenario EHP+EC can lead to the minimum operational cost, while the scenario DH+EC can lead to the minimum primary energy consumption. The GHP+GAC scenario is the one that may lead to the highest energy and cost objective function values with the defined set of parameters.

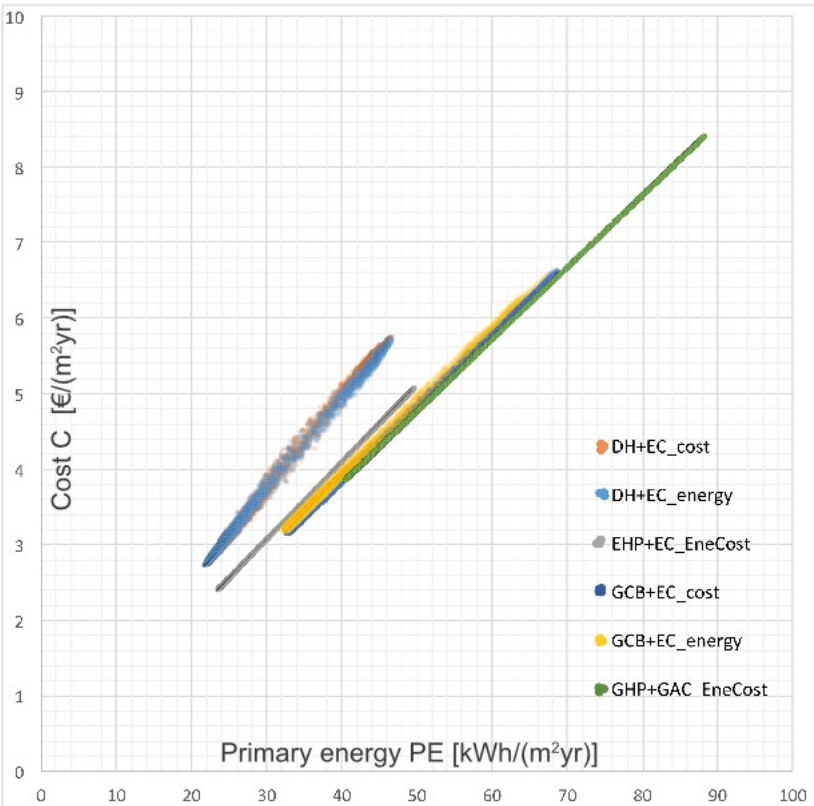

Figure 7. Primary energy (x-axis) and cost (y-axis) values of the points of the design space that were evaluated within optimization processes in all scenarios.

The results representation in Figure 8 shows the position of the clouds of points with respect to the different *loci* of optimal points resulting from the different scenarios. The Qc/Qh ratios and the objective function values for each of the optimal points for each scenario are reported in Table 9.

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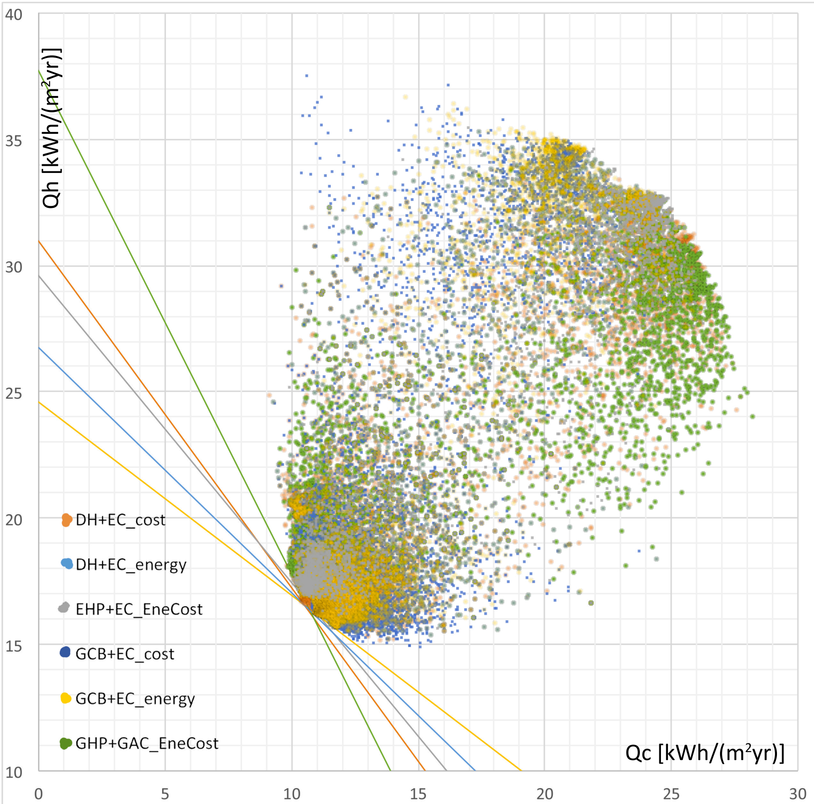

Figure 8. Qc (x-axis) and Qh (y-axis) values of the points of the design space that were evaluated within the optimization in all scenarios.

Table 9. Objective function values and Qc/Qh ratio of optimal solutions (energy and cost) in all scenarios.

Scenario	**Point**	**Qc/Qh ratio**	**PE kWh/m²**	**C €/m²**	**PE range (max-min) kWh/m²**	**C range (max-min) €/m²**
DH+EC_Energy	INI	0.51	35.4	4.56		
	Eopt	0.62	21.6	2.74	21.8	
	Copt	0.67	21.8	2.73		3.02
GCB+EC	Eopt	0.74	32.4	3.17	36.8	
	Copt	0.67	32.5	3.15		3.48
GHP+GAC	ECopt	0.56	40.3	3.84	47.8	4.61
EHP+EC	ECopt	0.60	23.3	2.39	26.6	2.69

As mentioned above, Figure 9 reports the ranges of Q_c/Q_h ratios related to the building design configurations within the optimum neighborhoods for the different scenarios and objectives. The black lines represent the absolute optimum points in their neighborhood and the black dots report the value of the w_c/w_h ratios of each corresponding scenario. As expected, there is an inverse correlation between the w_c/w_h ratio and the Q_c/Q_h ratio of the optimal solutions, as the higher the first, the lower the second and vice-versa.

Comparing the different scenarios, it appears that there is a smaller range of Q_c/Q_h ratios falling within the optimum neighborhood of all scenarios (it is between the two red lines in Figure 9). This means that there is a set of building design configurations that are optimal or nearly-optimal, regardless of the system scenario or the optimization objective.

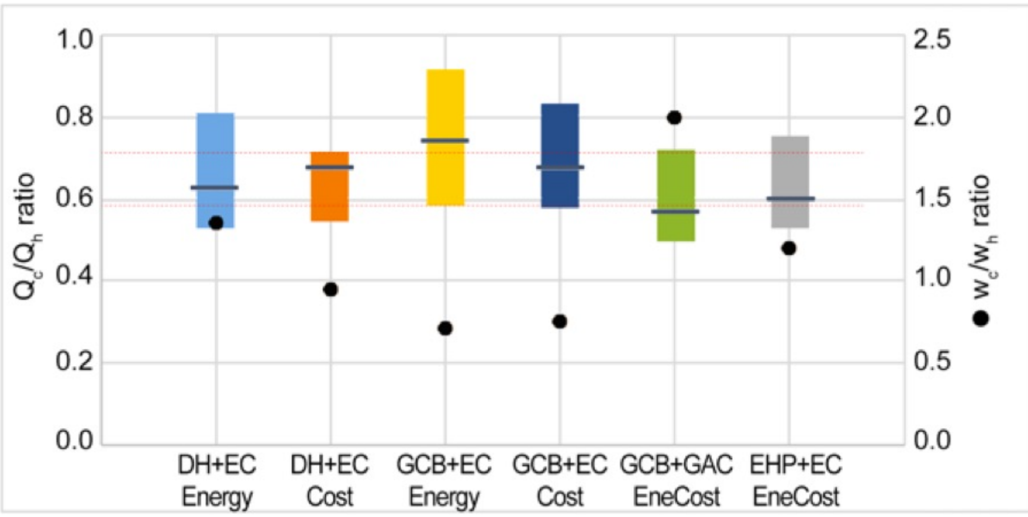

Figure 9. Range of Q_c/Q_h ratio related to the optimum neighborhood in relation to the w_c/w_h ratio of each system scenario.

In order to analyze the parameter values associated to the points in the optimum neighborhoods leading to the above-presented ranges of Q_c/Q_h, the distribution of frequency of the values assumed by each parameter in the optimum neighborhood has been studied in Figures 10, 11, 12. These figures report, on the vertical axes, all the values within the range of variation of each design parameter; on the horizontal axis, the frequency of occurrence of each value within the set of solutions composing the optimum neighborhood. The different colors refer to the different scenarios as in previous Figures.

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This allows the resilience of the optimal building design configuration (the set of optimal parameter values) to the variation of the system scenario and objective to be analyzed. On the other side, the fact that more than one parameter value is possible for reaching similar objective function values opens more possibilities to the designer who can select one or the other design configuration according to other constraints.

As shown in Figure 10, the parameters related to wall insulation appear to be the most resilient, as almost 100% of points within the optimum neighborhoods in all scenarios have the same values for wall insulation parameters. Also, the parameters related to the external wall solar absorption coefficients and the window types have a most frequent value, but there are a significant number of points with different values.

The design parameters related to the dimensions of windows and shadings are the less resilient, as their values can be combined in different ways within the optimum neighborhoods.

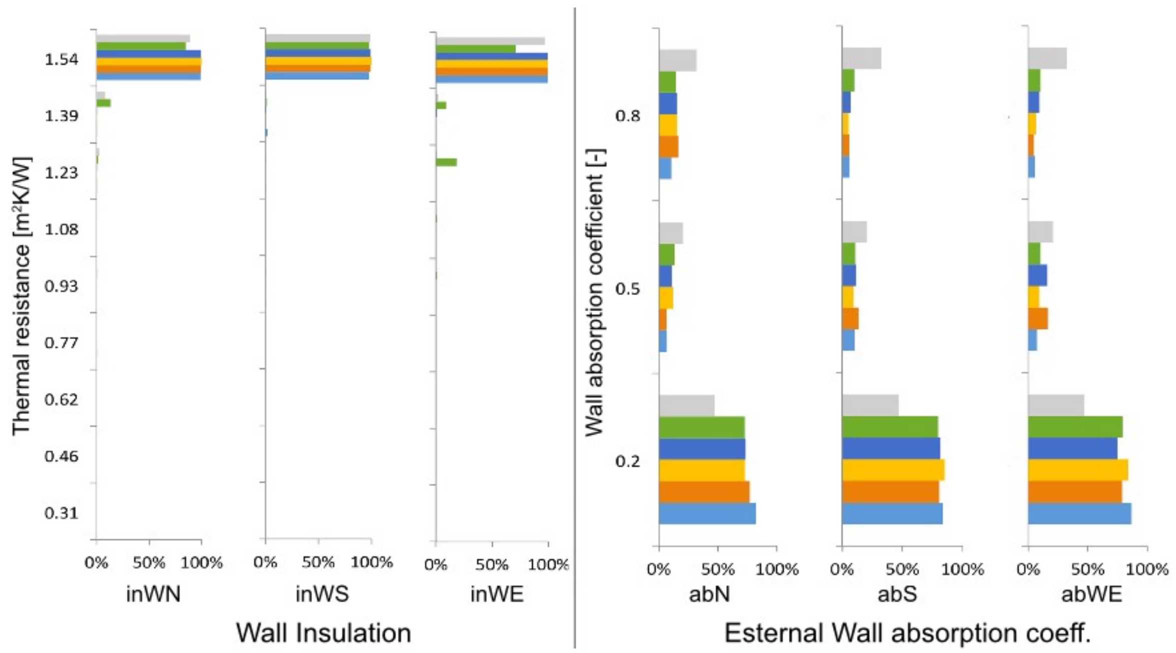

Figure 10. Distribution of parameter values within the optimum neighborhoods/1

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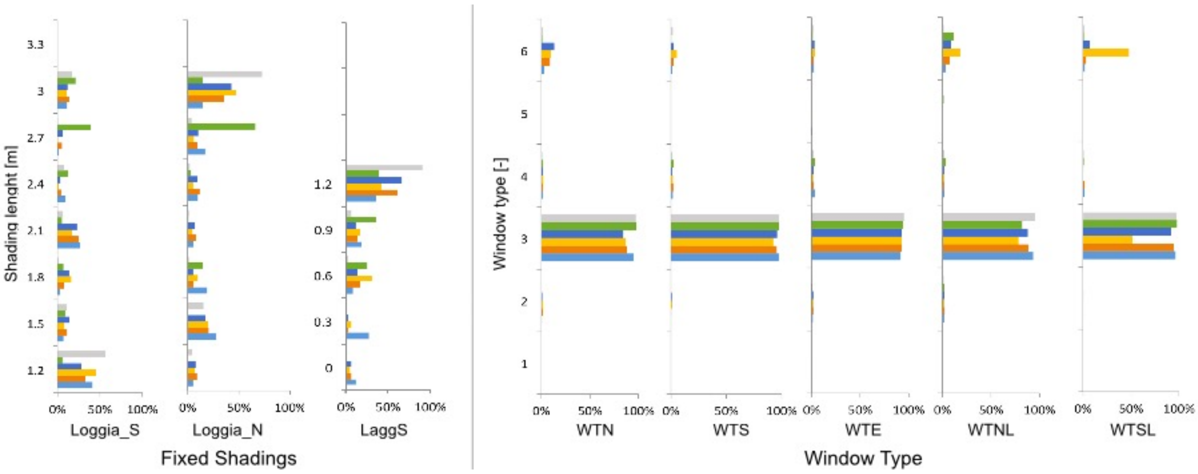

Figure 11. Distribution of parameter values within the optimum neighborhoods/2

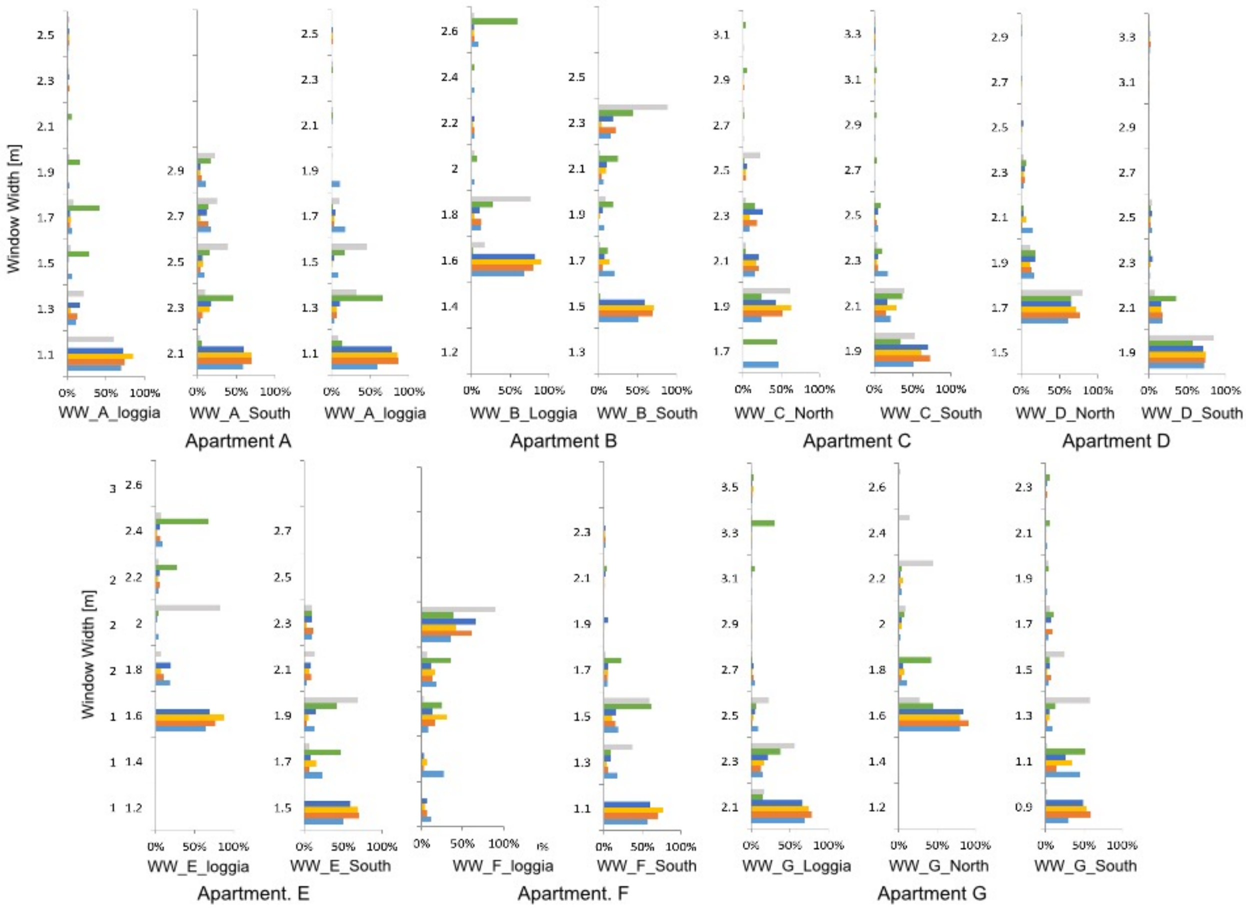

Figure 12. Distribution of parameter values within the optimum neighborhoods/3

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5. Conclusions

This study deals with the envelope design optimization (passive energy efficiency measures) of a recent multi-family building for social housing in Italy according to different objectives (non-renewable primary energy consumption and operational costs) and different energy system scenarios. With the defined design parameters, based on the current design of the building, both the energy optimization and the cost optimization can decrease the sum of heating and cooling primary energy consumptions by more than 35% and the energy costs for heating and cooling by around 35%. This demonstrates that there is still a large potential for performance improvement with respect to the current construction practice of multi-family buildings in Italy.

This has a significant impact on the design, since performance improvements derive from increasing the wall insulation, from selecting window types with an optimal combination of thermal transmittance and solar factor according to the orientation, from modifying the depth of loggias, with obvious implications on the flat layout, and from adding fixed shadings elements of a specific depth, with implications on the façade design.

It was demonstrated that the extent to which the cost-optimized design differs from the energy-optimized design depends on the adopted system scenario. In fact, depending on such scenarios, different weights are assigned to the heating and cooling needs in the two objective functions (energy and cost). When the system scenario implies the use of more than one energy carrier, it is expected that the energy-optimized design is different from the cost-optimized design, because the ratio between the weights in the energy objective function differs from the cost weight ratio. In these cases, it was found that the performance improvements achieved in both the energy-optimized and the cost-optimized scenarios are very close to each other, but the optimal design solutions result in a different ratio between cooling and heating energy demands. This means that a different optimization objective may transform a cooling-driven optimization process into a heating-driven process or vice versa. On the other side, in the scenarios using only one energy carrier, the energy-optimized design is also cost-optimized and the optimal solution depends only on the adopted system scenario. It has to be pointed out that, in this study, the non-renewable primary energy conversion factor was used to compute the energy weights. The differences between energy and cost optimization would change if total primary energy or delivered energy were used, because they would lead to different weighting ratios. However, because this study only considers energy supply from the grid and not from in-situ renewable energy production systems, only small differences would be appraised, as shown in a preliminary study (Ferrara, 2017b).

Moreover, it was demonstrated that the optimum neighborhood contains many different design solutions that lead to energy and cost values very close to the optimum. A great number of design alternatives that are almost equivalent in terms of performance can better support the design process in dealing with other constraints that are not specifically related to the energy design of the building. Furthermore, it was found that there is a set of design solutions that are included in the optimum neighborhood of all the analyzed scenarios. This provides a set of design alternatives that are very close to the energy optimum and, at the same time, are able to reduce the vulnerability of low-income tenants living in multi-family buildings while being resilient to the possible future variation of the energy system scenario.

Within this set of solutions in the optimum neighborhood, the optimal values of parameters related to the wall insulation and the window type appear to be the most robust in all scenarios.

It has to be noted that these results were achieved by optimizing the floor as a whole. Better results could be probably achieved by optimizing the performance of each apartment, but investigations on how to deal with the possible increase of construction costs due to a greater differentiation of construction components should be done.

Further work should complete the study and investigate the problem from the building owner perspective, including also the investment and maintenance costs in the cost objective function. Other developments will expand the design space considering design variables related to the building envelope, to the energy systems and to on-site renewable energy sources at the same time. Future developments of the work will investigate the problem in different weather conditions and in different energy tariff scenarios.

Nomenclature

Acronyms

DH	District Heating
EC	Electric Chiller
EHP	Electric Heat Pump
GAC	Gas Absorption Chiller
GCB	Gas Condensing Boiler
GHP	Gas Heat Pump
INI	Initial building configuration
OPT	Optimal building configuration
PSO	Particle Swarm Optimization algorithm

Latin letters

abN	solar absorption coefficient of external wall – North façade
abS	solar absorption coefficient of external wall – South facade
abWE	solar absorption coefficient of external wall – West, East facades
Blr	Width of the window at the ground floor on the south façade (m)
Bm	Width of the window at the first floor on the south façade (m)
C	Operational cost (€)
c	specific energy cost (€/kWh)
f_{pe}	primary energy conversion factor
inWN	Thermal resistance of wall insulation – North façade (m^2K/W)
inWS	Thermal resistance of wall insulation – South façade (m^2K/W)
inWE	Thermal resistance of wall insulation – West, East facades (m^2K/W)
Loggia_N	Depth of North loggia (m)
Loggia_S	Depth of South loggia (m)
Lagg_S	Depth of fixed shadings on the South façade windows (m)
OF	Objective function

PE	Primary Energy (kWh)
p	Parameter
s	Parameter variation step
Q	Energy need (kWh)
w	weight
WTE	Window Type of East,West facades (-)
WTN	Window Type of North facade (-)
WTNL	Window Type of North loggia facade (-)
WTS	Window type of South facade (-)
WTSL	Window Type of South loggia facade (-)
WW	Window width (m)

Subscripts

c	cooling
h	heating

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