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Energy-optimized versus cost-optimized design of high-performing dwellings: The case of multifamily buildings

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1   # Energy-optimized vs. cost optimized design of high-performing dwellings:
2   # the case of multi-family buildings
3
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8

9   **Abstract**

10
11   Living in multi-family buildings is very common in Italy and it is important to optimize the design

12   strategies to minimize the energy demand of these buildings and their related operational costs. This

13   is particularly important for low-income tenants, and is pursued by many social housing

14   developments where a good energy performance design is reached. In this work, a simulation-based

15   optimization methodology that combines the use of TRNSYS® with GenOpt® is applied in order to

16   minimize two objective functions - the annual primary energy demand and the operational energy

17   cost - in different system technology scenarios, and verify the differences between energy-optimized

18   design and cost-optimized design in a northern Italy climate. The study is performed on a typical

19   floor of a real multi-family building for social housing. The envelope optimization demonstrates a

20   potential reduction of the energy demand and cost for heating and cooling of more than 35%. The

21   relationship between optimal solutions, system technology scenarios and optimization objectives is

22   deeply analyzed. It is possible to find a set design solutions that are optimal in all the analyzed

23   scenarios. This provides a set of design alternatives that are close to the environmental optimum and

24   are able to reduce the low-income tenants vulnerability.

25   **Keywords:** simulation-based optimization; multi-family building; social housing; energy
26   system technology scenarios, operational cost
27

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 CO_2 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.

52   In the literature, such studies adopt either quasi steady-state energy assessment models compliant

53   to EN ISO 13790 (Kapsalaki et al, 2012; Ferreira et al., 2016) or dynamic simulation models (Wang

54   et al. 2011; Bayraktar et al, 2012) when the selection and comparison of design alternatives is either

55   manual or automated. However, the development of building dynamic simulation and its combination

56   with automated optimization has been recognized as a powerful tool for designers to evaluate

57   thousands of different building design solutions (Xing et al., 2016). This allows the building design

58   to be accurately optimized according to different objective functions, which entails the dynamic

59   calculation of the building energy consumption as a starting point.

60   Depending on the aim of the study, the choice of the optimization objective can vary between

61   primary energy minimization, global cost or life cycle cost minimization, thermal or visual comfort

62   maximization, etc., but it is important to consider that this choice clearly affects the resulting building

63   design. Also, the techno-economic scenario in which the building is optimized is affected by

64   uncertainty and it is necessary to consider multiple scenarios in order to find robust solutions

65   (Rysanek et al, 2013).

66   Many researchers are dealing with the problem of developing strategies for the economic

67   feasibility of energy-optimal building design, as there is often a gap between the economic optimum

68   and the zero (or positive) energy target (Ferrara et al., 2014; Pikas et al, 2015; Zacà et al, 2015).

69   Energy and cost are indeed the two objectives that are most frequently addressed in the literature.

70   34% of studies related to the building design optimization problems (Evins, 2013) deal with the

71   energy objective, while cost objectives are addressed in around 30% of the studies. Among those

72   addressing cost optimization, only 20% focus on operational costs. In fact, the majority of such

73   studies add up investment, maintenance, replacement and operational costs occurring within the

74   building lifecycle in the so-called global cost objective function. This is because the European

75   Directive 2010/31/EU has introduced the cost-optimal methodology as a tool for defining the energy

76   performance level leading to the lowest global cost within the building economic lifecycle.

77   The cost-optimal methodology is often adopted in a context where the building owner is also the

78   building user. In this situation, the building owner can optimize his investments and operational costs

79   in order to minimize the global cost over a defined time period. In this perspective, the operational

80   cost may often be hidden within the value of the global cost. This is the case of most of the studies

81   dealing with the cost-optimal methodology application (Kurnitski et al. 2011, Tronchin et al. 2012,

82   Tronchin et al., 2014, Pikas et al., 2017).

83   When dealing with social housing, however, the building owner, who is also the investor, is

84   different from the building user. In this context, different financial models may be applied and special

85   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

87   The design space in which the building has to be optimized depends on the considered design

88   variables. These variables may be related to the building envelope, not only in terms of construction,

89   but also in terms of geometry and facade design, or to the energy system, in terms of technology and

90   design, or both. For example, some authors (Prando et. al., 2015; Brandao de Vasconcelosa et al.,

91   2016) considered only variables related to the building envelope, such as window type, insulation

92   thickness and shading type. Other authors (Ascione et al. 2016, Monetti et al. 2015) compared

93   different technologies for heating and cooling energy supply.

94   Some of the building design optimization studies considered both envelope and energy systems,

95   assuming that these two groups of design variables are strictly interrelated. This was proven for a

96   single-family building (Ferrara et. al, 2016a), where it was demonstrated that the choice of the

97   building system influences the optimal design of the building envelope variables. However, very few

98   studies investigated this problem in relation to the more complex multi-family buildings design.

99   *1.3. Aim of the present work*

100   This work presents a replicable simulation-based optimization methodology to study in deep the

101   multi-family building design optimization problem in the Italian context.

102   The envelope-related design variables affecting the building heating and cooling energy needs are

103   identified and optimized in different heating and cooling systems scenarios, addressing separately the

104   non-renewable primary energy demand and the operational cost minimization objectives. The study

105   defines an economic objective function exclusively based on the operational cost for heating and

106   cooling as relevant for the social housing model, where low-income tenants are more interested in

107   low energy operational cost.

108   A theoretical framework for properly weighting the heating and cooling energy needs according

109   to the different objectives and system scenarios is presented, aiming at exploring the dependence of

110   the optimal design solution on such objectives and scenarios.

111   It is expected that reducing energy needs also reduces the operational costs, however, due to

112   differences in the weighting terms related to the energy or cost objectives, the energy-optimized and

113   the cost-optimized building design may not be the same. In fact, the resulted optimal solutions are

114   investigated in order to understand how and to what extent the two optimal design configurations

115   differ one from the other. The energy optimum, which minimizes the primary energy demand and

116   CO_2 emissions of the multi-family building, is compared to the economic optimum that will be

117   preferable in the tenants' perspective.

118   Further considerations about the influence of the energy supply system scenario in the

119   determination of such optimal solutions will be provided together with a study on the resilience of

120   the design variables to the variation of the optimization objectives and/or the system scenario.

121   The analysis is based on a case-study that is representative of new construction for social housing

122   in Italy and the findings of the study could inform the current design practice.

123
124

125 ## 2. Simulation-based methodology

126 *2.1. The optimization process*

127 The methodology that is proposed involves the coupling between a dynamic energy simulator and an

128 optimizer in a simulation-based optimization process. Among the available tools for simulation-based

129 optimization, the presented methodology relies on TRNSYS® as simulation tool and GenOpt® as

130 optimization tool, as shown in Figure 1.

131
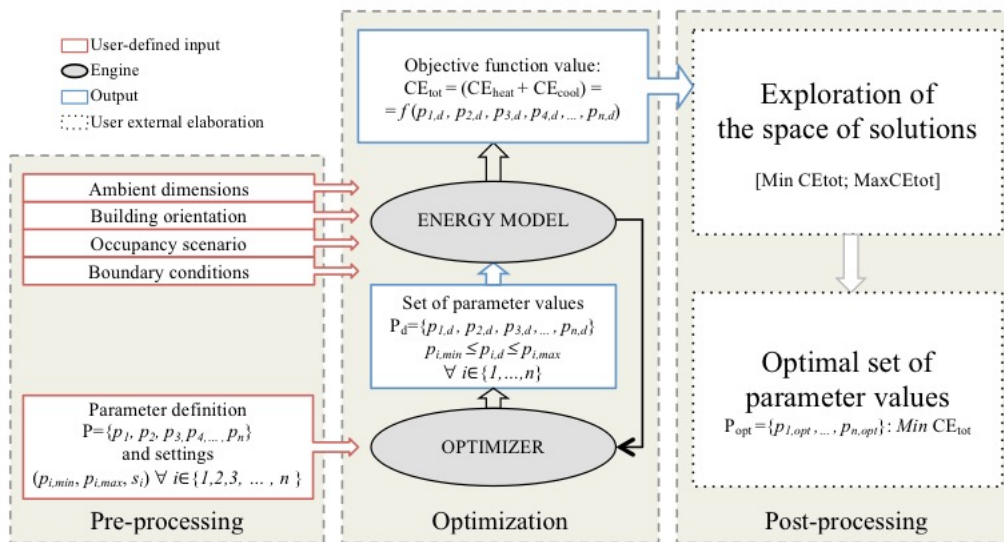
132

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

134

135 In the pre-processing stage, the TRNSYS model is created including the building boundary

136 conditions, and the set of design parameters is defined.

137 In the optimization stage, the iterative process driven by a PSO optimization algorithm leads to

138 evaluate a great number of design solutions, each related to a different set of parameter values, until

139 the objective function is minimized. The PSO is chosen for its ability to deal with discrete variables

140 in building design problems (Ferrara, 2017a). The output of the optimization stage is a big dataset

141 containing, for each solution that was evaluated within the process, the objective function value, the

142 parameter values that are related to each objective function and other secondary functions related to

143 that set of parameter values. The post-processing includes the exploration of the space of solutions

144 contained in that dataset and of the optimal set of parameter values that is associated to the minimized

145 objective function.

146 *2.2. Statement of the optimization problem*

147 As mentioned above, the purpose of this study is to compare the energy optimization against the

148 operational energy costs optimization of the design of a multi-family building.

149 The set of possible design options is the n-dimensional design space that is defined by the **P** set of n

150 user-defined parameters p, where $p_{i,d}$ denotes a value assumed by the parameter p_i in a potential

151 design solution d. Each parameter p represents a design variable that is able, by varying, to affect the

152 objective function of the optimization.

153 The values assumed by such parameters may vary in a discrete space according to the number of steps

154 $s_{i,max}$, numbered with consecutive integers from 0 to $s_{i,max}$, in which the space between the lower

155 and upper bounds $p_{i,min}$ and $p_{i,max}$ of each parameter variation range is divided. Based on this, $p_{i,d}$

156 denotes the value assumed by the parameter p_i corresponding to the step number $s_{i,d}$.

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

158

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

160 minimize $OF = Q_h(\mathbf{P}) \cdot w_h(T_{h,k}) + Q_c(\mathbf{P}) \cdot w_c(T_{c,j})$ $k \in \{1,2,\dots,l\}$

161 $j \in \{1,2,\dots,m\}$ (1.2)

162   where $P = \{p_1, p_2, p_3, \dots, p_n\} \subset \mathbb{Q}^n$ (1.3)

163 subject to $p_{i,min} \leq p_{i,d} \leq p_{i,max}$ $\forall i \in \{1,2,3,\dots,n\}$ (1.4)

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

165

166   where Q_h is the annual energy demand for space heating and Q_c is the annual demand for space

167   cooling, both evaluated by the dynamic simulation tool; $T_{h,k}$ and $T_{c,j}$ are related to the technical

168   system that is used for supplying the heating and the cooling energy, respectively. The terms w_h and

169   w_c are the weighting terms of the heating and cooling energy demands that are used for computing

170   the objective function *OF*.

171   *2.3. Definition of the objective functions*

172   For the purpose of this study, two different optimization processes have to be carried out separately,

173   one optimizing the energy performance and the other optimizing the operational energy cost.

174   Therefore, two objective functions have to be defined.

175   For the energy optimization, the objective function is the annual specific non-renewable primary

176   energy demand for heating and cooling. In this case, the weighting terms in Eq. (1.2) are computed

177   as follows

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

178

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

179

180   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

181   and cooling supply, depending on the adopted energy conversion technology. The terms $f_{T_{h,k}}$ and

182   $f_{T_{c,j}}$ represent the primary energy conversion factors related to the energy carriers that are used by

183   the selected energy systems. It has to be pointed out that such conversion factors usually differ from

184   one European Member State to the others, depending on the characteristics of the national energy

185   production and supply systems.

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

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

187

188   Concerning the cost optimization, the objective function is the specific annual operational costs for

189   space heating and cooling. The weighting terms of Eq. (1.2) are computed as follows

190

$$w_{h,cost} = \frac{c_{T_{h,k}}}{\eta_{T_{h,k}}} \tag{4.1}$$

191

$$w_{c,cost} = \frac{c_{T_{c,j}}}{\eta_{T_{c,j}}} \tag{4.2}$$

192   where $c_{T_{h,k}}$ and $c_{T_{c,j}}$ are the average annual prices of one kWh for space heating and cooling,

193   depending on the energy carrier used in the technical systems, and $\eta_{T_{h,k}}$ and $\eta_{T_{c,j}}$ are the seasonal

194   efficiencies of the technical systems $T_{h,k}$ and $T_{c,j}$ as in Eq. (2.1-2.2).

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

196

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

197   Similarly to the primary energy conversion factors, also the average annual energy prices may vary

198   throughout Europe according to the tariff adopted by the energy suppliers and the different national

199   energy incentives policies.

200   Assuming that the present study is carried out in the Italian context, as shown above, the weighting

201   terms may vary according to the energy system technologies and the related energy carriers.

202   Therefore, in order to cover all the possible design solutions, the optimization process should be

203   repeated for each combination of energy systems that may be installed in the building that has to be

204   optimized.

205   After computing the weights for each of the selected systems for heating and cooling (w_h and w_c

206   respectively), the ratio w_c/w_h indicates the relative weight of the cooling terms to the heating term

207   (for example, a ratio equal to 2 indicates that the cooling energy demand weights two times the

208   heating demand and therefore the minimization of the objective function will be mostly cooling-

209   driven). It has to be noted that some systems for heating supply may not be combined with others for

210   cooling supply. In those cases, the scenario is defined as "not compatible". The creation of a matrix

211   (Table 1) helps identify the feasible solutions and therefore the weights to be given to the objective

212   functions to perform the optimization in multiple energy system scenarios.

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

	$w_{h,1}$	$w_{h,...}$	$w_{h,l}$
$w_{c,1}$	$w_{c,1}/w_{h,1}$	not compatible	$w_{c,1}/w_{h,l}$
$w_{c,...}$	$w_{c,...}/w_{h,1}$	$w_{c,...}/w_{h,...}$	not compatible
$w_{c,m}$	$w_{c,m}/w_{h,1}$	$w_{c,m}/w_{h,...}$	$w_{c,m}/w_{h,l}$

214

2.4. On the locus of optimal points

216   Based on previous considerations, the objective function of the above-presented problem is linear,

217   where Q_h and Q_c are the two independent variables, which depend, in turn, on the set of parameter **P**.

218   Therefore, each objective function value is associated to a certain ratio Q_h and Q_c values or, better, to

219   a set of Q_h,Q_c couples, as there may be different Q_h,Q_c couples leading to the same objective function

220   value. For the given objective function value, the relationship between the values of Qh and Qc may

221   be expressed, based on Eq (1.2), as follows

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

223   where OF is the selected objective function value (either cost or energy) and w_h and w_c are the related

224   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

225   to the minimum objective function value (OF_{opt}). On a bi-dimensional graph, as in Figure 2, where

226   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

227   following form

228                          $$y = -mx + q \qquad\qquad (7)$$

229   where, based on (6), the slope m is expressed by the w_c/w_h ratio, and the intercept q is expressed by

230   the OF_{opt}/w_h ratio.
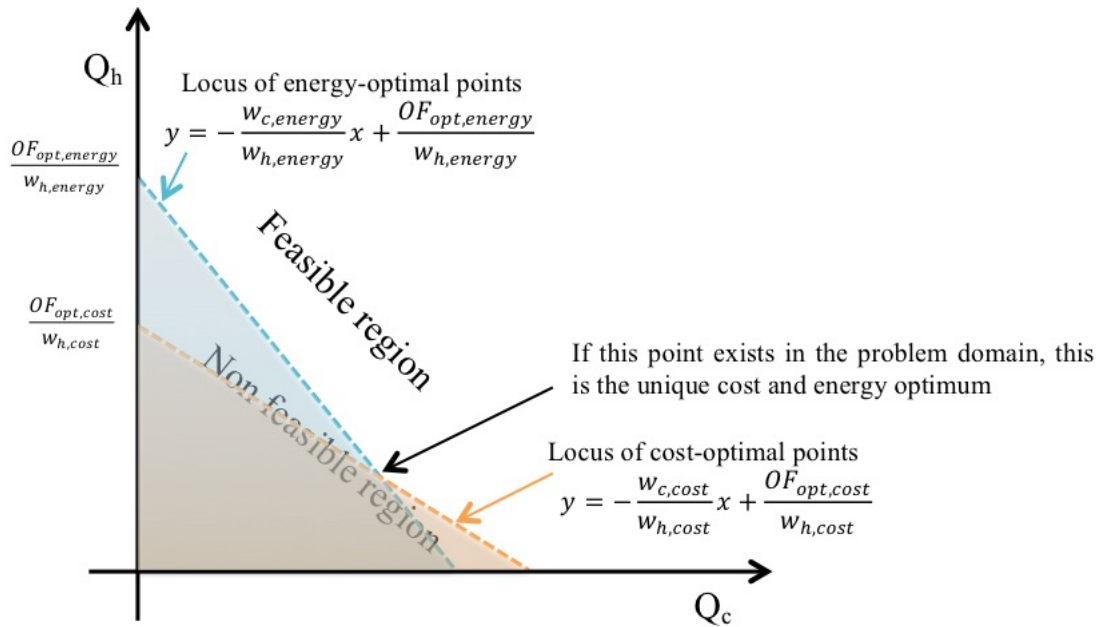
231

232   *Figure 2. Problem domain and locus of optimal points*

233

234   The domain of such function depends on the existence of the Q_h,Q_c couples, which depends on the

235   multi-dimensional space of points generated by the all possible sets of parameter **P**. The slope of this

236   line will be different for each system scenario, depending on the matrix of weights in Table 1. The

237   example reported in Figure 2 represents the case in which the ratio $\frac{w_{c,energy}}{w_{h,energy}}$ is greater than the ratio

238     $\frac{w_{c,cost}}{w_{h,cost}}$ but the opposite situation may occur.

239   For the same system scenario, the locus of cost-optimal points and the one of energy-optimal points

240   may have different slopes, according to their w_c/w_h ratios. In this case, the two lines will cross in a

241   unique point that is both the energy-optimal and cost-optimal solution, if that point is within the

242   problem domain (in other words, if the related Q_h,Q_c couple exists). Otherwise, this is only a

243   theoretical point and the energy-optimum and the cost-optimum will be in different positions on the

244   related lines (see Figure2).

245 **3. Application to a reference case-study**

246 *3.1. Case-study description: initial scenario*

247 The case study is a real multi-family building that is representative of new construction for social

248 housing in Northern Italy (degree days between 2100 and 3000). The whole 6-floors building is

249 composed of 35 apartments of different sizes, for a total net floor area of 2330 m^2.

250 External walls are made of a layer of bricks (30 cm) with external thermal insulation (10 cm), for a

251 wall thermal transmittance U equal to 0.26 W/(m^{2}K). The mean thermal transmittance of the

252 transparent surfaces is equal to 1.45 W/(m^{2}K), which is related to double low-e glass windows with

253 metal frame. The solar factor is 0.59. As shown in Figure3, there are fixed shadings on the facades,

254 including balconies and loggias, which are typical features of Italian construction. Additional details

255 on the case study building features are in (Ferrara et al. 2016b).

256 For the purpose of this work, one typical floor of the case study building was selected for carrying

257 out optimization studies. As reported in Figure 3, the floor is composed of 7 apartments, having

258 different floor areas and surface-to-volume ratios (Table 2), for a total conditioned floor area of

259 466 m^2.

260

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

263   Table 2 reports the specific primary energy consumption and the operational costs related to each

264   apartment and to the entire floor. These values refer to the building actual configuration, which is the

265   so-called "initial scenario" for the optimization.

266   *Table 2. Initial scenario. Annual primary energy consumption and annual energy costs for each*
267   *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

268

269   The primary energy and the costs in such scenario were calculated considering a district heating

270   system for heating supply ($T_{h,ini}$) and electric chillers for cooling supply ($T_{c,ini}$). Therefore the

271   efficiencies, the primary energy factors and the energy costs are defined as follows

272   • $\eta_{T_{h,ini}}$=0.88, based on the building Energy Performance Certificate;

273   • $f_{h,ini}$=0.62, as declared by the district heating supplier (the district heating system in that

274   area combines heat generation from waste, from a co-generation plant and from a biomass

275   source);

276   • $\eta_{T_{c,ini}}$=2.05, Italian reference efficiency for electric chillers (DM 26/06/2015);

277   • $f_{c,ini}$=1.95, Italian non-renewable primary energy conversion factor for electricity

278   (DM 26/06/2015);

279   • $c_{h,ini}$=0.09 €/kWh$_{th}$ (Linea Reti e Impianti, 2016);

280   • $c_{c,ini}$=0.20 €/kWh$_{el}$ (Eurostat, 2016).

281   An electric mechanical ventilation system with a heat exchanger is also used, where the mean

282   seasonal efficiency of the sensible heat recovery is 0.5.

283   The energy simulations for calculating Q_h and Q_c were carried out with the IWEC weather data for

284   Piacenza (weather station 160840, which is the closest to the actual building location).

285   The primary energy demands for DHW and ventilation were not included in the optimization, as they

286   are not affected by the building envelope design. However, they were calculated with simplified

287   methods in order to estimate the weight of heating and cooling on the total energy demand. The

288   primary energy and cost for DHW were calculated according to the Italian Standard UNI/TS 11300-

289   2 and considering a gas condensing boiler (η_{DHW} =0.85, f_{DHW}=1.05, c_{DHW}=0.08 €/kWh$_{th}$). The

290   primary energy and cost for ventilation (respectively EP$_v$ and C$_v$) represent the electrical energy use

291   and the related cost for handling of the ventilation air. They are derived considering a 0.5Wh/m^3

292   specific installed power factor, as indicated for the Italian reference building in DM 26/06/2015, and

293   0.20 €/kWh$_{el}$ as electricity cost.

294   As shown in Table 2 the energy rating, according to the current Italian energy performance

295   certification regulation (DM 26/06/2015), is A1 for each apartment and for the entire floor.

296   *3.2. Definition of the optimization parameters and the objective functions*

297   As described in the statement of the optimization problem, the set of design variables and their range

298   and step of variation delineate the design space to be explored within the optimization process. In this

299   study, this process aims at investigating possible performance improvements of a reference multi-

300   family building without changing its layout. Therefore, the optimization parameters were selected

301   among the design variables of the building envelope that may affect the energy needs, while the

302   building geometry and the apartments layout are fixed to their actual configuration.

303 As shown in Table 3, the selected design variables are related to the thermal resistance of the

304 insulation panels and to the solar absorption coefficient of the external walls, to the type and size of

305 the windows, to the horizontal overhang and fins dimensions of South-oriented windows, to the depth

306 of the loggias facing North and South. The range and the step of their variation were set according to

307 regulation requirements, technical feasibility and market criteria. In the Nomenclature, all the defined

308 parameters are reported.

309 *Table 3. Project parameters description*

Parameter Name	Description	unit	min	max	step	Initial value
sISOLN	North walls - thermal resistance insulation	m^{2}K/W	1.12	5.40	0.53	1.65
sISOLEW	East/West walls - thermal resistance insulation	m^{2}K/W	1.12	5.40	0.53	1.65
sISOLS	South walls - thermal resistance of insulation	m^{2}K/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

310

311 Table 4 reports the selected options for variation of window type parameters, which are related to

312 different combinations of glass thermal transmittance, solar factor and visible transmittance. The set

313   of parameters, with their dimension and constraints, defines the space of solutions of the problem, in

314   which the search of the optimal design solutions may be conducted with different objectives.

315

Table 4. Options for window type parameters

ID	Glazing	U_g (W/m²K)	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

316

317   As mentioned above, different energy system technologies for heating and cooling have been

318   considered in the study, leading to different formulation of the objective functions, based on

319   Equations (3) and (5). Table 5 lists them and shows the main data assumed in the study, as follows:

320   • η_{gen} represents the reference seasonal energy efficiency for each generation system (DM

321   26/06/2015);

322   • $\eta_{T_{h,k}}$ and $\eta_{T_{c,k}}$ represent the seasonal global energy efficiency for the heating and cooling

323   energy systems as the generation efficiency multiplied by a 0.82 standard utilization factor

324   that takes into account the efficiency of the distribution, the emission and the regulation

325   systems;

326   • $f_{T_{h,k}}$ and $f_{T_{c,k}}$ represent the Italian non-renewable primary energy conversion factors of the

327   specific energy carrier for heating and cooling supply;

328   • w_{energy} is the energy weight factor as defined in Eq. (2.1) and (2.2);

329   • $c_{T_{h,k}}$ and $c_{T_{c,k}}$ are the specific costs of the kWh related to the energy carriers of the heating

330   and cooling energy systems;

331   • w_{cost} is the cost weight factor as defined in Eq. (4.1) and (4.2).

332

333

334 *Table 5. Efficiencies and weights related to the technical systems for heating and cooling supply*
335 *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

336

337 The combination of different energy system technologies for heating and cooling generates the four

338 main scenarios considered in the study, each of them characterized by specific weighting factors to

339 compute the objective functions for the optimization.

340

341 *3.3. Optimization runs*

342 For each energy system scenario, the optimization process was run both for minimizing and for

343 maximizing the objective functions, so that at the final stage, as post-processing, the space of solution

344 could be explored from its minimum to its maximum.

345 The GenOpt binary version of the PSO algorithm (Wetter, 2011), based on the performance study

346 reported in (Ferrara, 2017), was run with the following settings: 20 particles, social acceleration set

347 to 2.5, cognitive acceleration set to 1.5, maximum velocity equal to 4. The random seed was set to 1

348   and the Von Neumann neighborhood topology was used with a size of 5. Each optimization was run

349   until 150 generations are reached.

350   The four energy system scenarios are defined as follows:

351   • Scenario 1 corresponds to the initial scenario characterized by a District Heating system for

352   heating supply and an Electric Chiller for cooling supply;

353   • Scenario 2 is characterized by the combination of a Gas Condensing Boiler for heating

354   supply and an Electric Chiller for cooling supply;

355   • Scenario 3 is characterized by the combination of a Gas Heat Pump for heating supply and a

356   Gas Absorption Chiller for cooling supply;

357   • Scenario 4 is characterized by the combination of a Electric Heat Pump for heating supply

358   and an Electric Chiller for cooling supply;

359   The resulting weights w_c, w_h and the ratio w_c/w_h (in colors) for each scenario are reported, based on

360   the structure of Table 1, for both the energy objective function (Table 6) and the cost objective

361   function (Table 7).

362

363

364   *Table 6. The matrix of the total energy weight w_c/w_h of each the design scenario for the*
365   *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

366

367

368

369

370

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

373

374 Where, for a specific scenario, the $w_{c,energy}/w_{h,energy}$ ratio equals the $w_{c,cost}/w_{h,cost}$ ratio, the two

375 optimization processes run for minimizing primary energy and cost are expected to lead to equal

376 results. In fact, each optimal solution is characterized by an optimal Q_c/Q_h ratio related to the

377 minimum objective function value. Each different w_c/w_h ratios will lead to different opimal Q_c/Q_h

378 ratios. The difference between the energy and cost optimization for a same system scenario can be

379 explained by the difference between the related energy and cost w_c/w_h ratios. Therefore, it is

380 expected that the greater the difference between w_c/w_h ratios, the biggest differences between the

381 energy-optimized design and the cost-optimized design will be appraised.

382

383 **4. Results and discussion**

384 Results are presented into three types of diagrams. The first type (e.g. Figure 4) reports on the

385 horizontal axis the energy objective function (3), representing the specific annual non-renewable

386 primary energy need of the case-study floor. The cost objective function (5), representing the specific

387 annual energy cost in euros per square meter of conditioned floor area, is reported on the vertical axis.

388 The second type (e.g. Figure 5) reports the specific energy need for space cooling (Q_c) on the

389   horizontal axis and the specific energy need for space heating (Q_h) on the vertical axis. In these

390   graphs, each point represents one building design configuration associated to one combination of

391   parameter values. The points that were found within the same optimization process, for the same

392   system scenario and objective function, are clustered in clouds where points have the same color (e.g.

393   Figure 8), according to the colors used in Table 6 and Table 7.

394   The third type of graph (e.g. Figure 10) reports on the vertical axes the range of variation of the

395   parameter values and on the horizontal axis the frequency distribution of those values within the

396   solution in the optimum neighborhoods.

397   A detailed results analysis is reported for the Scenario 1, then results related to the other scenarios

398   are summarized and compared.

399

400   *4.1. Scenario 1: detailed analysis of results*

401   Figure 4 reports all points evaluated within the optimization processes in Scenario 1 (DH+EC) with

402   the two objectives. The points of the design space that were evaluated within the energy optimization

403   process are reported in blue, while orange points are referred to the cost optimization process. As

404   shown, these points are part of the same design space, which was searched through in different ways

405   according to the optimization objective. Since the optimization process was run for both minimizing

406   and maximizing the objective functions, the graph shows that the range of possible solutions led to

407   primary energy values within the range 21.6-46.7 kWh/(m^2yr) and to operational energy cost values

408   in the range between 2.7 and 5.8 €/(m^2yr).

409   The black dot indicates the position of the initial building design in the initial scenario. It is shown

410   that both the primary energy demand for space heating and cooling and the operational energy costs

411   can be reduced by around 40%.

412
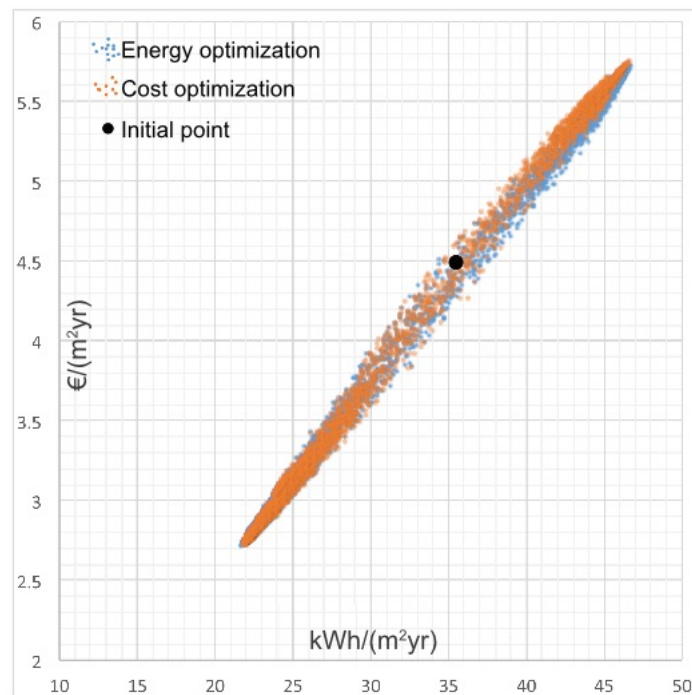
Figure 4. Primary energy (x-axis) and cost (y-axis) values of the points of the design space that were evaluated within the energy optimization (blue) and the cost-optimization (orange) in scenario 1.

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.

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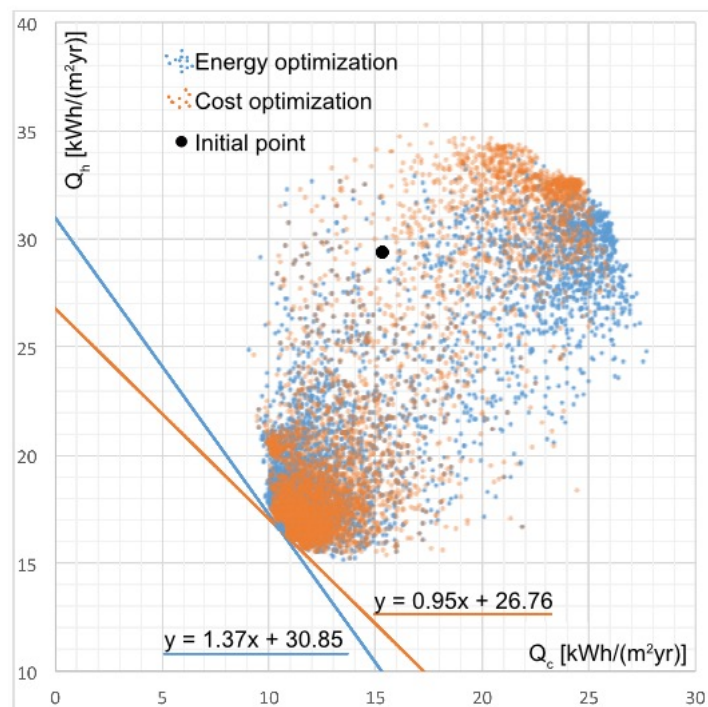
Figure 5. Qc (x-axis) and Qh (y-axis) values of the points of the design space that were evaluated within the energy optimization (blue) and the cost-optimization (orange) in Scenario 1.

429
430

431

432 However, in the neighborhood of optimum, there is still a significant set of design alternatives leading

433 to similar objective function values, as shown in Figure 6, where a zoom on the optimal region of

434 Figure 5 is reported. The objective function value to be considered as the upper bound of the optimum

435 neighborhood was set to the minimum objective function value increased by 5% of the difference

436 between the minimum and the maximum objective function values (max-min range).

437 As shown in Figure 6, the optimal points for the two objective functions (the points laying on the

438 respective *loci* of optimal points) are quite close to the crossing point of the two lines, but they do not

439 exactly correspond to that point. This means that there are two different Qc/Qh couples that are related

440 to the two optimal points, each corresponding to a different optimal design configuration.
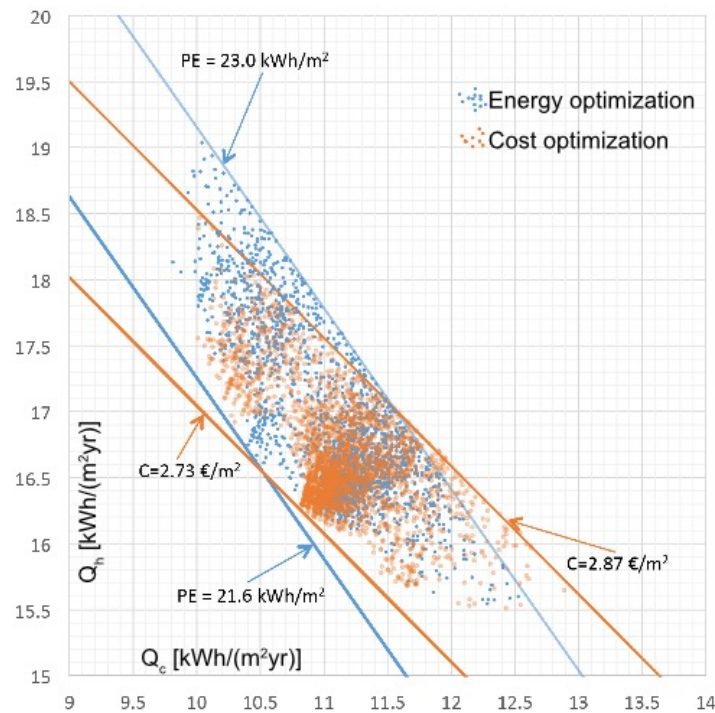
Figure 6. Neighborhood of the optimal points in Scenario 1.

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.

458 *Table 8. Objective function and parameter values in the initial scenario and in the two optimal*
459 *solutions (energy and cost). The grey color indicates the parameters of which the optimal value*
460 *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

461

462 In the last rows of Table 8, the Qc/Qh ratio referred to the initial point (INI), the energy optimum

463 (Eopt) and the cost optimum (Copt) points are reported.

464 Beyond the resulted absolute objective function values, which may be affected by uncertain modeling

465 assumptions, the most interesting result is related to the wide range of possible building design

466 configuration leading to objective function values in the optimum neighborhood. Within this

467 neighborhood, the variety of design solutions, and thus of different combinations of parameter values,

468 is demonstrated by the range of Qc/Qh ratios. For the system Scenario 1, the Qc/Qh ratio of the points

469 in the optimum neighborhood ranges from 0.53 to 0.8 for the energy optimization and from 0.54 to

470 0.73 for the cost optimization. These ranges are reported below in Figure 9, together with those related

471 to the other system scenarios.

472   *4.2. All scenarios: results summary and resilience of the optimum*

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

474   The variations of the max-min ranges of objective function values related to the system scenarios are

475   shown in Figure 7. It is clear that the scenario EHP+EC can lead to the minimum operational cost,

476   while the scenario DH+EC can lead to the minimum primary energy consumption. The GHP+GAC

477   scenario is the one that may lead to the highest energy and cost objective function values with the

478   defined set of parameters.
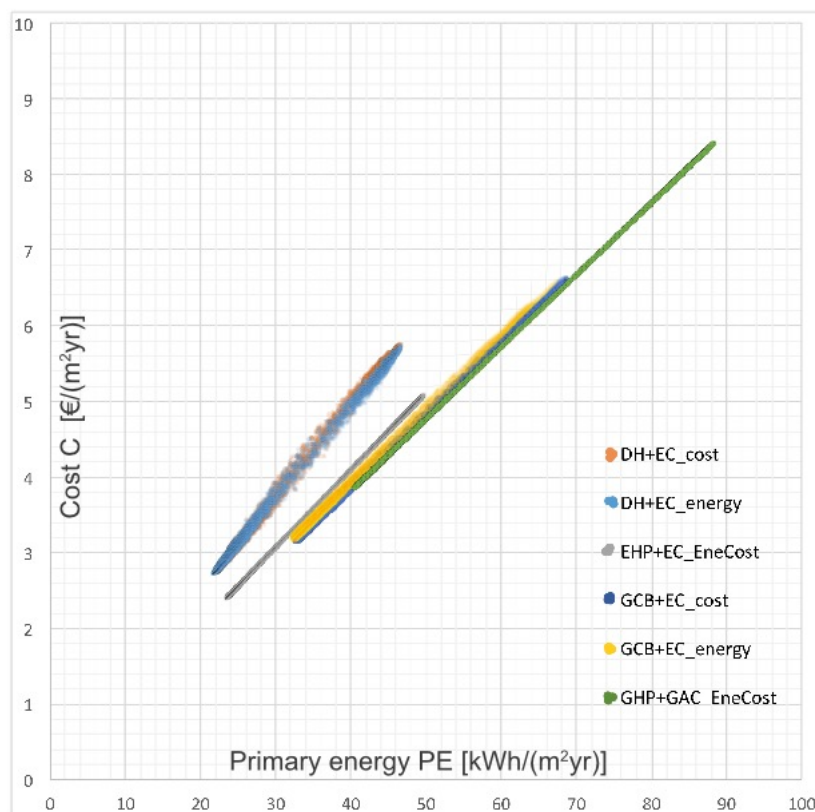
479

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

482

483   The results representation in Figure 8 shows the position of the clouds of points with respect to the

484   different *loci* of optimal points resulting from the different scenarios. The Qc/Qh ratios and the

485   objective function values for each of the optimal points for each scenario are reported in Table 9.

486

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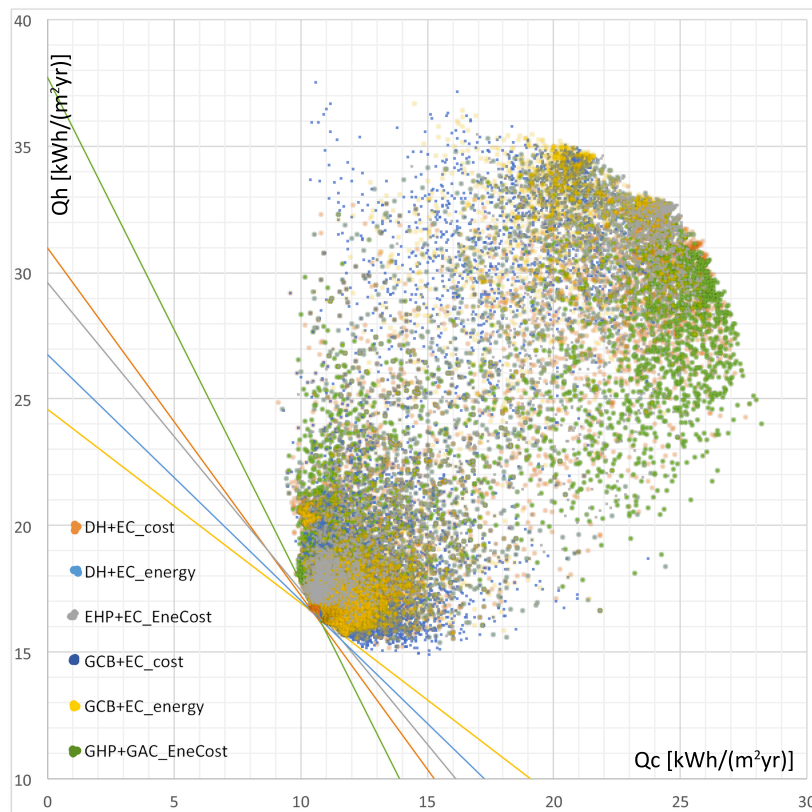
Figure 8. Qc (x-axis) and Qh (y-axis) values of the points of the design space that were evaluated within the optimization in all scenarios.

490

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

499

500 As mentioned above, Figure 9 reports the ranges of Q_c/Q_h ratios related to the building design

501 configurations within the optimum neighborhoods for the different scenarios and objectives. The

502 black lines represent the absolute optimum points in their neighborhood and the black dots report the

503 value of the w_c/w_h ratios of each corresponding scenario. As expected, there is an inverse correlation

504 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

505 the second and vice-versa.

506 Comparing the different scenarios, it appears that there is a smaller range of Q_c/Q_h ratios falling within

507 the optimum neighborhood of all scenarios (it is between the two red lines in Figure 9). This means

508 that there is a set of building design configurations that are optimal or nearly-optimal, regardless of

509 the system scenario or the optimization objective.

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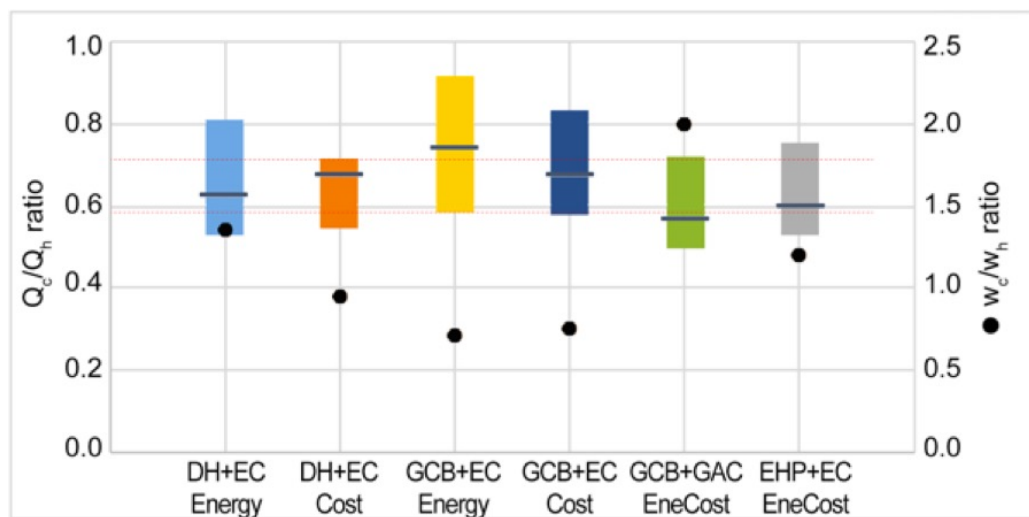
511

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

514

515 In order to analyze the parameter values associated to the points in the optimum neighborhoods

516 leading to the above-presented ranges of Q_c/Q_h, the distribution of frequency of the values assumed

517 by each parameter in the optimum neighborhood has been studied in Figures 10, 11, 12. These figures

518 report, on the vertical axes, all the values within the range of variation of each design parameter; on

519 the horizontal axis, the frequency of occurrence of each value within the set of solutions composing

520 the optimum neighborhood. The different colors refer to the different scenarios as in previous Figures.

521   This allows the resilience of the optimal building design configuration (the set of optimal parameter

522   values) to the variation of the system scenario and objective to be analyzed. On the other side, the

523   fact that more than one parameter value is possible for reaching similar objective function values

524   opens more possibilities to the designer who can select one or the other design configuration

525   according to other constraints.

526   As shown in Figure 10, the parameters related to wall insulation appear to be the most resilient, as

527   almost 100% of points within the optimum neighborhoods in all scenarios have the same values for

528   wall insulation parameters. Also, the parameters related to the external wall solar absorption

529   coefficients and the window types have a most frequent value, but there are a significant number of

530   points with different values.

531   The design parameters related to the dimensions of windows and shadings are the less resilient, as

532   their values can be combined in different ways within the optimum neighborhoods.
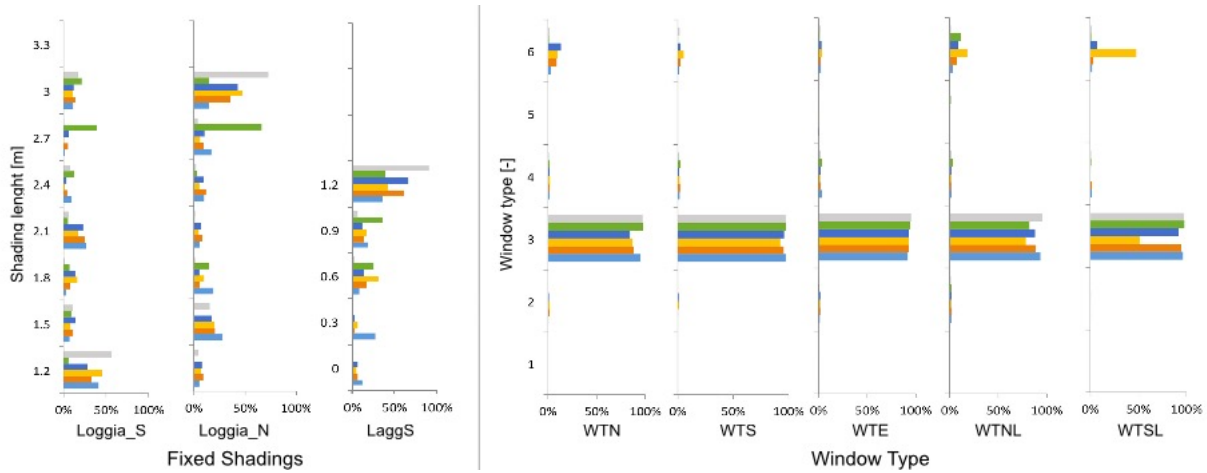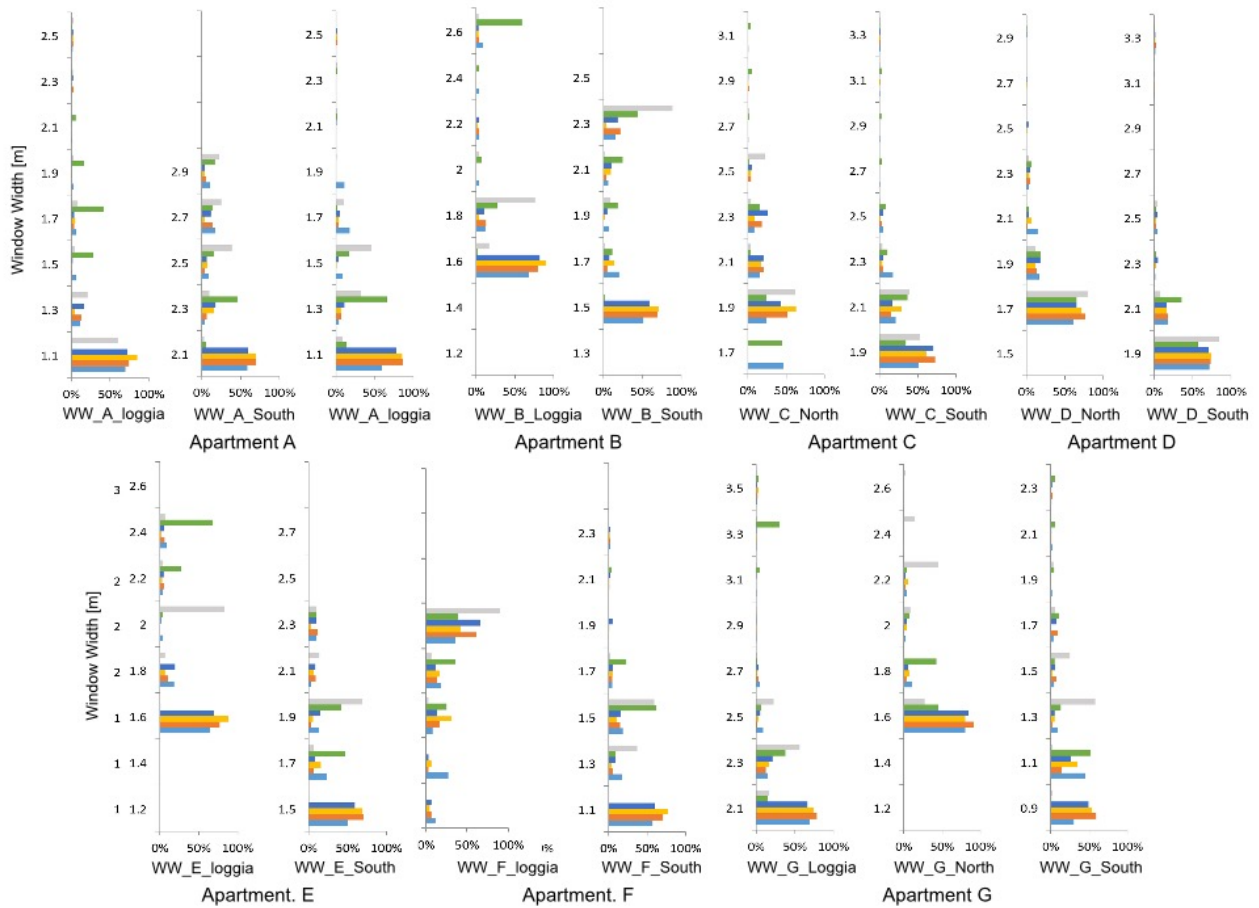
533
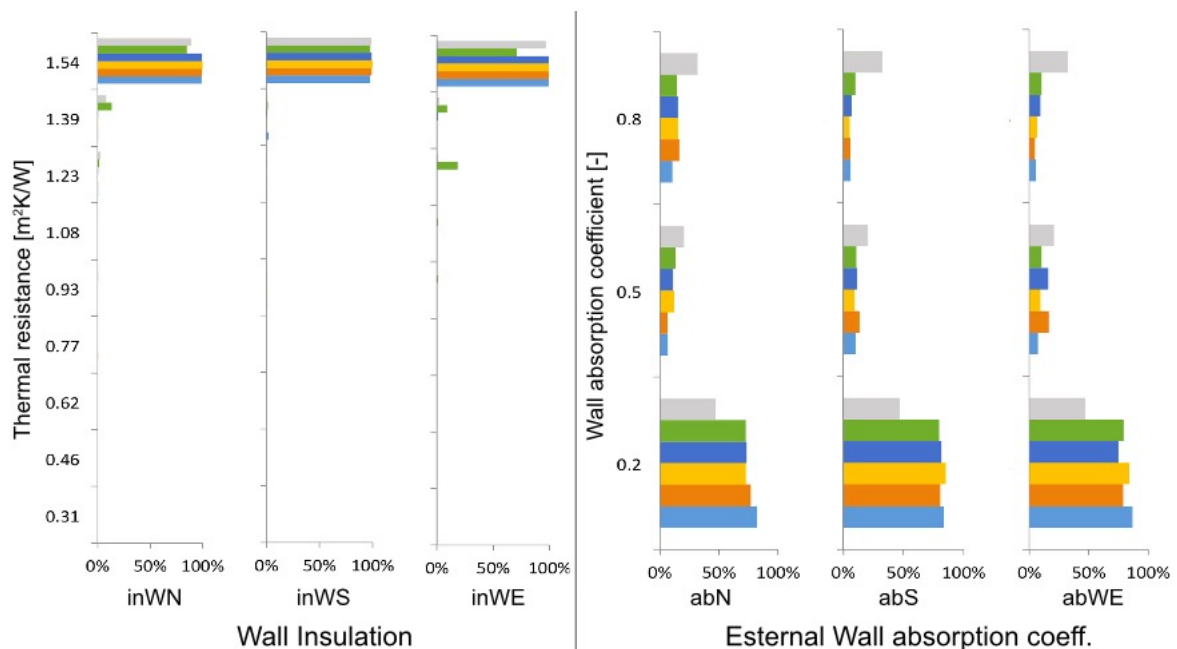
Figure 10. Distribution of parameter values within the optimum neighborhoods/1

536

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

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

543 **5. Conclusions**

544 This study deals with the envelope design optimization (passive energy efficiency measures) of a

545 recent multi-family building for social housing in Italy according to different objectives (non-

546 renewable primary energy consumption and operational costs) and different energy system scenarios.

547 With the defined design parameters, based on the current design of the building, both the energy

548 optimization and the cost optimization can decrease the sum of heating and cooling primary energy

549 consumptions by more than 35% and the energy costs for heating and cooling by around 35%. This

550 demonstrates that there is still a large potential for performance improvement with respect to the

551 current construction practice of multi-family buildings in Italy.

552 This has a significant impact on the design, since performance improvements derive from increasing

553 the wall insulation, from selecting window types with an optimal combination of thermal

554 transmittance and solar factor according to the orientation, from modifying the depth of loggias, with

555 obvious implications on the flat layout, and from adding fixed shadings elements of a specific depth,

556 with implications on the façade design.

557 It was demonstrated that the extent to which the cost-optimized design differs from the energy-

558 optimized design depends on the adopted system scenario. In fact, depending on such scenarios,

559 different weights are assigned to the heating and cooling needs in the two objective functions (energy

560 and cost). When the system scenario implies the use of more than one energy carrier, it is expected

561 that the energy-optimized design is different from the cost-optimized design, because the ratio

562 between the weights in the energy objective function differs from the cost weight ratio. In these cases,

563 it was found that the performance improvements achieved in both the energy-optimized and the cost-

564 optimized scenarios are very close to each other, but the optimal design solutions result in a different

565 ratio between cooling and heating energy demands. This means that a different optimization objective

566 may transform a cooling-driven optimization process into a heating-driven process or vice versa. On

567 the other side, in the scenarios using only one energy carrier, the energy-optimized design is also

568   cost-optimized and the optimal solution depends only on the adopted system scenario. It has to be

569   pointed out that, in this study, the non-renewable primary energy conversion factor was used to

570   compute the energy weights. The differences between energy and cost optimization would change if

571   total primary energy or delivered energy were used, because they would lead to different weighting

572   ratios. However, because this study only considers energy supply from the grid and not from in-situ

573   renewable energy production systems, only small differences would be appraised, as shown in a

574   preliminary study (Ferrara, 2017b).

575   Moreover, it was demonstrated that the optimum neighborhood contains many different design

576   solutions that lead to energy and cost values very close to the optimum. A great number of design

577   alternatives that are almost equivalent in terms of performance can better support the design process

578   in dealing with other constraints that are not specifically related to the energy design of the building.

579   Furthermore, it was found that there is a set of design solutions that are included in the optimum

580   neighborhood of all the analyzed scenarios. This provides a set of design alternatives that are very

581   close to the energy optimum and, at the same time, are able to reduce the vulnerability of low-income

582   tenants living in multi-family buildings while being resilient to the possible future variation of the

583   energy system scenario.

584   Within this set of solutions in the optimum neighborhood, the optimal values of parameters related to

585   the wall insulation and the window type appear to be the most robust in all scenarios.

586   It has to be noted that these results were achieved by optimizing the floor as a whole. Better results

587   could be probably achieved by optimizing the performance of each apartment, but investigations on

588   how to deal with the possible increase of construction costs due to a greater differentiation of

589   construction components should be done.

590   Further work should complete the study and investigate the problem from the building owner

591   perspective, including also the investment and maintenance costs in the cost objective function. Other

592   developments will expand the design space considering design variables related to the building

593   envelope, to the energy systems and to on-site renewable energy sources at the same time. Future

594   developments of the work will investigate the problem in different weather conditions and in different

595   energy tariff scenarios.

596

597   **Nomenclature**

598   *Acronyms*

599   DH   District Heating

600   EC   Electric Chiller

601   EHP   Electric Heat Pump

602   GAC   Gas Absorption Chiller

603   GCB   Gas Condensing Boiler

604   GHP   Gas Heat Pump

605   INI   Initial building configuration

606   OPT   Optimal building configuration

607   PSO   Particle Swarm Optimization algorithm

608

609   *Latin letters*

610   abN   solar absorption coefficient of external wall – North façade

611   abS   solar absorption coefficient of external wall – South facade

612   abWE   solar absorption coefficient of external wall – West, East facades

613   Blr   Width of the window at the ground floor on the south façade (m)

614   Bm   Width of the window at the first floor on the south façade (m)

615   C Operational cost (€)

616   c   specific energy cost (€/kWh)

617   f_{pe} primary energy conversion factor

618   inWN   Thermal resistance of wall insulation – North façade (m²K/W)

619   inWS   Thermal resistance of wall insulation – South façade (m²K/W)

620   inWE   Thermal resistance of wall insulation – West, East facades (m²K/W)

621   Loggia_N   Depth of North loggia (m)

622   Loggia_S   Depth of South loggia (m)

623   Lagg_S   Depth of fixed shadings on the South façade windows (m)

624   *OF*   Objective function

625	*PE*	Primary Energy (kWh)
626	*p*	Parameter
627	*s*	Parameter variation step
628	*Q*	Energy need (kWh)
629	w	weight
630	WTE	Window Type of East,West facades (-)
631	WTN	Window Type of North facade (-)
632	WTNL	Window Type of North loggia facade (-)
633	WTS	Window type of South facade (-)
634	WTSL	Window Type of South loggia facade (-)
635	WW	Window width (m)
636		
637	Subscripts	
638	*c*	cooling
639	*h*	heating
640		

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