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Influence of envelope design in the optimization of the operational energy costs of a multi-family building

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Abstract

The international efforts for improving energy efficiency in buildings and reducing their environmental impact also constitute a challenge for working against the risk of energy poverty. The work aims to test a methodology for optimizing the operational costs of the different flats of a multi-family building for social housing. The method combines the use of TRNSYS building energy simulation program with GenOpt Generic Optimization program in a so-called simulation-based optimization method.
A typical floor of a real case study building was modeled and the energy costs for heating and cooling due to the variation of design variables related to the building envelope was studied. The optimization led to reduce the total operational costs of the flats by the range 17%-23%. The different share of heating, cooling, ventilation and DHW in the total operational costs was studied and resulted differences in energy rating and costs between flats were analyzed.

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Keywords: simulation-based optimization; multi-family building; social housing; TRNSYS; GenOpt; particle swarm; flats; operational costs

1. Introduction

In the residential sector. improving the energy efficiency of new and existing buildings can be useful not only for contrasting CO_2 emissions and climate change, but also for working against the risk of energy poverty for low-income households. It has been proved that financial problems may oblige people to consume less energy, leading to the incomplete satisfaction of their needs [1]. As reported in [2], it can be observed that during the financial crisis of 2007– 2012 in Europe, the energy consumption of residential buildings has decreased by 4%, while in countries with

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a deeper economic problem like Portugal, Slovakia and Ireland the corresponding decrease was 16%, 22% and 22% respectively. In Italy, it is estimated that between 5% and 20% of households was in energy poverty in 2012 [3].

This problem is frequent for multi-family buildings. In 2014, 5 out of every 10 persons in Italy lived in flats [4]. Within a more comprehensive approach towards the implementation of economic sustainability principles [5], it emerges the importance of considering the effect of the design strategies in the total energy demand of multi-family buildings and their related operational costs, even more so if addressed to low-income households. In fact, reduced exposure to energy price fluctuations gives the user a feeling of control and increased certainty to be able to keep the needed level of comfort while maintaining economic affordability. Furthermore, especially in case of social housing, reducing the differences between flats within the same building leads to highest equality between families.

The use of tools able to evaluate and optimize the building energy performance by analyzing a great number of different design configurations is emerging as a powerful method for supporting this design process [6].

1.1. Scope of the work

The aim of the work is to apply a simulation-based optimization methodology [7] to assess the potential reduction of the annual operational energy costs for heating and cooling of a multi-family building for social housing in Italy.

The optimization process focuses on energy efficiency measures able to reduce the operational costs for heating and cooling of each flat of the case study floor. With the addition of the costs related to DHW and ventilation fans, the work also evaluates the potential reduction of the total energy costs (for heating, cooling, DHW, ventilation) due to the adopted optimization process.

2. Case study

In order to study a multi-family building that is representative of recent social housing intervention in Italy, a real building located in Cremona was selected. Because of its features that are recurrent in similar buildings throughout Italy, the analysis can be potentially replicated in other Italian contexts.

It has a C shaped plan around a common inner courtyard. Each block has different number of storeys. The building has a concrete structure and a well-insulated envelope. External wall is made of bricks (30cm) and external thermal insulation (10 cm) with a thermal transmittance U equal to 0.26 W/m^{2}K. Transparent surfaces are double low-e glass windows with metal frame, having mean thermal transmittance equal to 1.45 W/m^{2}K and a solar factor equal to 0.59. Some windows are shaded by external loggias, a typical feature of the Italian architecture.

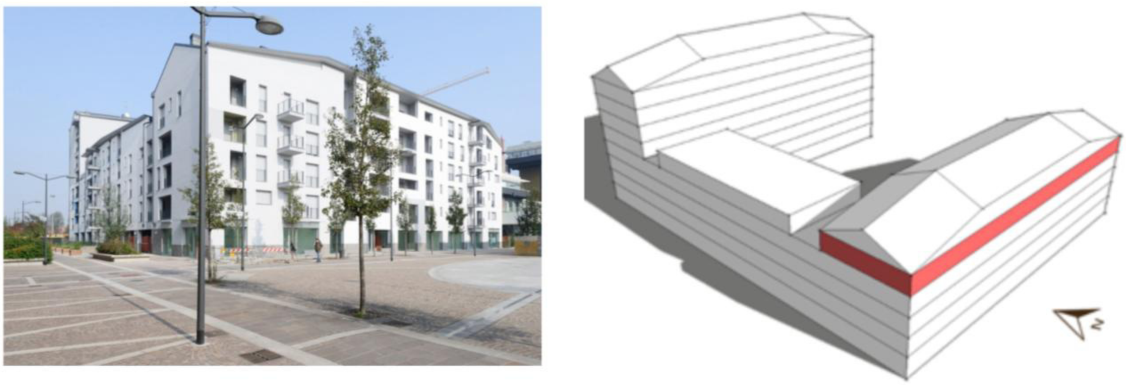

Fig. 1. (a) The multi-family building (b) The case study floor

The building is connected to a district-heating network supplied by a municipal solid waste incinerator that delivers hot water for heating (total primary energy conversion factor declared by the supplier equal to 0.62). There are radiant panels as heating terminals. The total seasonal efficiency ratio of the heating system is equal to 0.88.

A gas boiler produces DHW (energy efficiency ratio 0.85, primary energy conversion factor 1.05).

A mechanical ventilation system with a heat exchanger with an efficiency equal to 0.50 is also present.

The analyzed part of the building corresponds to the red storey in Fig. 1; it is the fifth floor with North-South prevailing orientation, composed of seven flats with different shapes and dimensions. The net floor area of the conditioned volume considered into the analysis is equal to 466 m^2. None of the seven units has thermal transmission upward and downward, since each flat is facing ceilings or floors of conditioned zones. As shown in Fig. 2, a letter from "A" to "G" was assigned to each flat, which was defined as a thermal zone. Their surface/volume ratios are very different and vary from 0.74 of "A" to 0.26 of "C" and "D". "E" and "F" are the only units to present only South-oriented external surfaces.

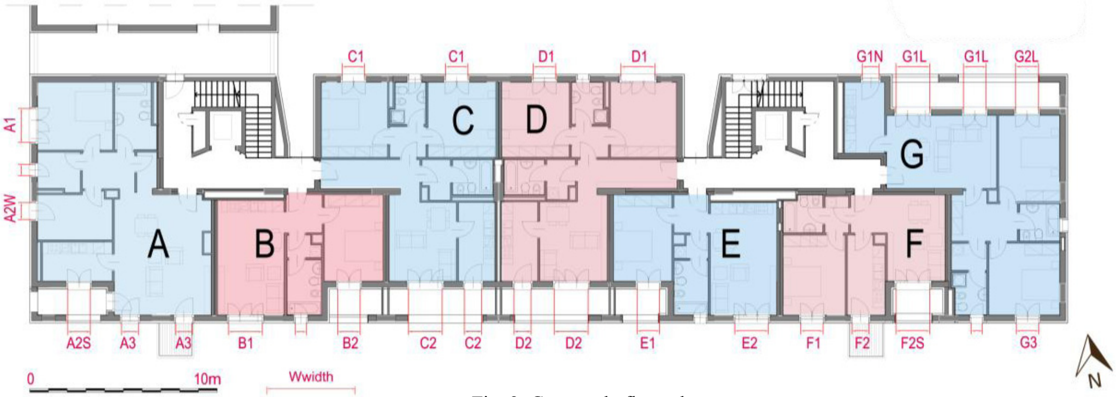

Fig. 2. Case study floor plan

Heating and cooling energy needs were calculated with a dynamic energy simulation tool (TRNSYS). In the real case, there is no cooling system. However, in order to be able to evaluate through simulation also the space cooling needs and the related costs, a reference air conditioner system with an energy efficiency ratio EER equal to 2.05 was considered (total primary energy conversion factor for electricity equal to 2.42). The energy demand for hot water and ventilation fans were calculated according to the Italian technical regulation UNI TS 11300 (monthly steady state calculations). The set-point temperatures for heating and cooling were set to 20°C and 26°C, respectively. The heating period was set from October 15th to April 15th with continuous operation, according to Italian regulations. In days outside the heating period, the cooling system is supposed to work when the temperature goes above the cooling set point temperature. Internal loads were set for each flat according to the Italian technical regulation UNI TS 11300, resulting in an average of 5.5 W/m^2 during the all day. No holidays periods were considered. The mechanical ventilation rate was set equal to 0.7 ach, based on the design data of the real building.

Based on the calculated energy demand, the operational costs for heating, cooling, DHW and ventilation fans were calculated for each flat of the case study floor. According to the current Italian energy tariffs, were set to 0.10 €/kWh$_t$ for the thermal energy provided by the district heating system, 0.08 €/kWh$_t$ for gas and 0.20 €/kWh$_e$ for electricity. Table 1 shows values of the operational energy costs of each flat and mean values for the entire floor.

Table 1. Annual energy costs for heating. cooling. DHW and mechanical ventilation

Zone	Su (m2)	S/V	€heat/m2	€cool/m2	€water/m2	€VMC/m2	€tot/m2	Energy rating
A	86.0	0.74	€ 4.27	€ 1.26	€ 1.58	€ 1.24	€ 8.35	A1
B	48.7	0.66	€ 2.85	€ 1.52	€ 1.80	€ 1.24	€ 7.41	A1
C	77.5	0.26	€ 3.10	€ 0.82	€ 1.62	€ 1.24	€ 6.78	A1
D	77.5	0.26	€ 3.04	€ 0.80	€ 1.62	€ 1.24	€ 6.70	A1
E	47.4	0.32	€ 2.50	€ 1.72	€ 1.82	€ 1.24	€ 7.28	A1
F	47.6	0.27	€ 2.20	€ 1.68	€ 1.82	€ 1.24	€ 6.94	A1
G	81.1	0.45	€ 4.34	€ 1.18	€ 1.60	€ 1.24	€ 8.36	A1
Tot. floor	465.8	0.46	€ 3.34	€ 1.22	€ 1.66	€ 1.24	€ 7.46	A1

The energy class, calculated according to the Italian regulation (DM 26/06/2015), is the same for all the flats (class A1). However, despite this uniformity in energy rating, differences occur when considering costs.

As shown, the mean operational energy costs for heating, cooling, DHW and ventilation fans for the floor are respectively 3.34 €/m^2, 1.22 €/m^2, 1.66 €/m^2, 1.24 €/m^2. Analyzing the performance of each flat respect to the mean values, great variations emerge especially for heating and cooling costs. In fact, the specific energy cost for heating may vary from -34% to +30% around the mean value, ranging from 2.20 €/m^2 to 4.34 €/m^2 and the specific energy cost for cooling varies in the range -34% - +41% around the mean value, ranging from 0.82 €/m^2 to 1.72 €/m^2. This is due to the different cooling and heating needs driven by differences in exposure and S/V ratio among flats.

Looking at the floor medium values, it is shown that the share of heating, cooling, DHW and ventilation in the total operational costs are 45%, 16%,22% and 17%, respectively. For all flats, the sum of the cooling and heating costs accounts for between 56% and 66% of the total. For that reason, considering all the energy uses, differences among operational energy costs of flats decrease. A maximum variation of 20% is attested. Flat G has the higher operational costs equal 8.36 €/m^2, instead flat D has the lower equal to 6.70 €/m^2.

3. Methods

The adopted simulation-based optimization methodology has been defined in previous studies and applied for the optimization of a detached house [8] and a school classroom [9]. This includes two main steps, that are the definition of the design parameters and the implementation of the automated optimization process for evaluating the potential reduction of the energy costs for heating and cooling of each flat of the floor case study, considering the interrelation between the defined design parameters. Adding to the analysis the operational energy costs related to DHW and ventilation fans, the effect of the optimization process on the total energy costs of each flat is evaluated.

3.1. Design parameters

As presented in Tables 2 and 3 and Fig. 2 and 3, the design parameters that were selected are the thermal resistance of the insulation panels and the solar absorption coefficient of the external walls, the type and size of the windows, the horizontal overhang and fins dimensions of South-oriented windows, the depth of the loggias facing North and South.

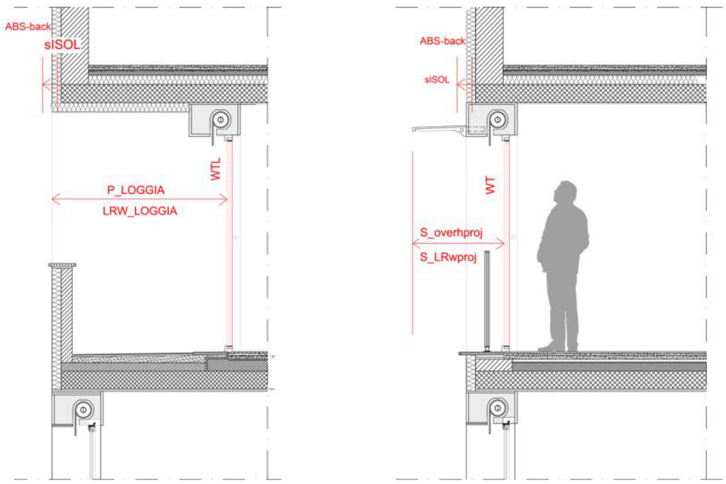

Fig. 3. Representation of envelope design variables defined as optimization parameters

These parameters were defined to allow a passive optimization of the building envelope without affecting the main architectural and morphological features of the building. In fact, the range and the step of their variation were set according to regulation requirements (e.g. the minimum window area is set to the limit imposed by the Italian regulation, the minimum insulation thickness is due to the thermal trasmittance requirements for external walls, etc.), technical feasibility (e.g. the maximum insulation thickness is set to the current technical practice, the maximum window width depends on the internal room dimensions, etc.) and market criteria (e.g. the window types are selected among those available on the market.

Table 2. Project parameters description

Parameter Name	Description	unit	min	max	step	Initial value
sISOLN	North walls - thermal resistance of the insulation layer	m^2Kh/kJ	0.31	1.5	0.17	0.48
sISOLEW	East/West walls - thermal resistance of the insulation layer	m^2Kh/kJ	0.31	1.5	0.17	0.48
sISOLS	South walls - thermal resistance of the insulation layer	m^2Kh/kJ	0.31	1.5	0.17	0.48
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	Overhang projection length for South windows	m	0.0	1.0	0.2	0.0
S_LRwproj	Left/right projection length for South windows	m	0.0	1.0	0.2	0.0
PLOGGIA	Overhang projection length for South loggia	m	0.0	2.7	0.3	1.8
LRw_LOGGIA	Left/right projection length for South loggia	m	0.0	2.7	0.3	1.8
PLOGGIAN	Overhang projection length for North loggia	m	0.0	2.7	0.3	1.8
LRw_LOGGIAN	Left/right projection length for North loggia	m	0.0	2.7	0.3	1.8
WT	North window type	-	1,2,3,4,5,6,7			1
WTS	South window type	-	1,2,3,4,5,6,7			1
WTW	West window type	-	1,2,3,4,5,6,7			1
WTL	Loggia window type	-	1,2,3,4,5,6,7			1
WWidthA1	Window width A1	m	1.0	2.6	0.2	1.0
WWidthA2W	Window width A2 Ovest	m	0.9	2.1	0.2	0.9
WWidthA2S	Window width A2 Sud	m	0.8	3.2	0.2	1.2
WWidthA3	Window width A3	m	1.8	4.0	0.2	1.8
WWidthB1	Window width B1	m	1.6	2.4	0.2	1.8
WWidthB2	Window width B2	m	1.2	2.6	0.2	1.2
WWidthC1	Window width C1	m	2.0	4.0	0.2	2.4
WWidthC2	Window width C2	m	2.7	4.9	0.2	2.7
WWidthD1	Window width D1	m	2.0	4.0	0.2	2.4
WWidthD2	Window width D2	m	2.7	4.9	0.2	2.7
WWidthE1	Window width E1	m	1.2	2.6	0.2	1.2
WWidthE2	Window width E2	m	1.6	2.0	0.2	1.8
WWidthF1	Window width F1	m	1.2	2.0	0.2	1.2
WWidthF2S	Window width F2 Sud	m	0.9	1.5	0.2	0.9
WWidthF2	Window width F2(Loggia)	m	1.6	2.6	0.2	1.8
WWidthG1N	Window width G1	m	0.9	1.5	0.2	0.9
WWidthG1L	Window width G1 (Loggia)	m	2.2	3.0	0.2	3.0
WWidthG2L	Window width G2	m	1.2	2.0	0.2	1.2
WWidthG3	Window width G3	m	1.0	3.0	0.2	1.2

Table 3. Parameters description. Window types.

Number	Num. ID Trnsys	Design	Ug (W/m²K)	g (-)	τ_l
1 (Initial)	2002	4/16/4	1.27	0.59	0.71
2	13002	4/15/4	1.10	0.61	0.78
3	12014	6/12/4/12/4	0.70	0.29	0.58
4	15001	6/16/6	1.10	0.33	0.64
5	3004	6/16/6	1.29	0.33	0.66
6	3001	2.5/12.7/2.5/12.7/2.5	2.00	0.70	0.74
7	12007	4/16/4/16/4	0.70	0.50	0.64

3.2. Optimization process

Since the objective is to minimize the total energy costs, based on the efficiencies of the energy system and the costs of the energy sources considered for the case study building (Par. 2), the objective function was set as

$$PE_{H+C} = \frac{Q_H}{\eta_H} \times c_H + \frac{Q_C}{EER} \times c_C = \frac{Q_H}{0.88} \times 0.10 + \frac{Q_C}{2.05} \times 0.20 \ [€] \tag{1}$$

The optimization process was performed through the coupling between TRNSYS and GenOpt. Among those available in GenOpt, the particle swarm optimization (PSO) algorithm was selected, because of its effectiveness in carrying out optimization with discrete variables [9]

The optimization process was run two times, firstly minimizing the objective function, then maximizing the objective function. In this way, the entire solution space, composed by the possible values that the objective function can assume with the set of parameters defined for this study, was assessed. This approach led to verify how large is the gap between the potential worst scenario and the potential optimal configuration and the location of the initial scenario between them.

4. Results

Results related to the optimization of the case study are shown in Fig.4.

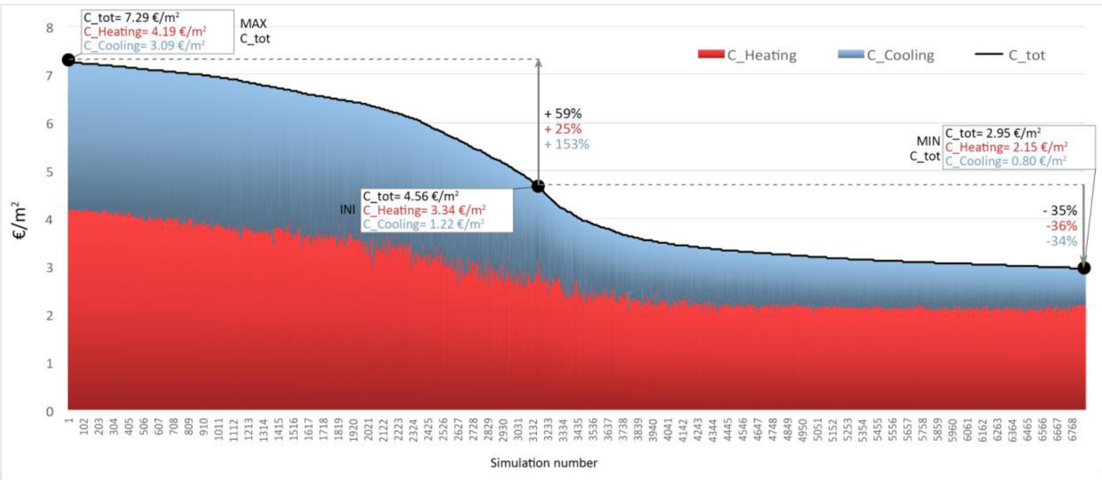

Fig. 4. Results of the optimization process.

All the objective function values, each related to one of the around 7000 different building configurations analyzed, were ordered from the maximum (MAX C_tot) to the minimum (MIN C_tot) value. The highest possible increase and decrease of the different energy demands with respect to the initial configuration (INI) are reported. The heating cost accounts for the highest share in all the evaluated values of the objective function but, because of the high cost of electricity, the highest variations are related to cooling costs. In the optimal value, the heating and cooling costs are reduced by almost the same amount, in terms of percentage.

Tables 4 and 5 show parameters values and cost calculations in the optimal scenario, respectively.

Table 4. Values assumed by the envelope design variables in the initial and optimal scenario.

Name	Initial value	Optimal value	unit	Name	Initial value	Optimal value	unit	Name	Initial value	Optimal value	unit
sISOLN	0.48	1.51	m2Kh/kJ	WT	1	3	-	WWidthD1	2.4	2.0	m
sISOLEW	0.48	1.51	m2Kh/kJ	WTS	1	7	-	WWidthD2	2.7	2.7	m
sISOLS	0.48	1.51	m2Kh/kJ	WTW	1	3	-	WWidthE1	1.2	1.2	m
abs-back	0.2	0.5	-	WTL	1	7	-	WWidthE2	1.8	1.6	m
abs-backS	0.2	0.2	-	WWidthA1	1.0	1.0	m	WWidthF1	1.2	1.2	m
abs-backEW	0.2	0.5	-	WWidthA2W	0.9	0.9	m	WWidthF2S	0.9	0.9	m
S_overhproj	0	0.6	m	WWidthA2S	1.2	0.8	m	WWidthF2	1.8	1.6	m
S_LRwproj	0	0.6	m	WWidthA3	1.8	1.8	m	WWidthG1N	0.9	0.9	m
PLOGGIA	1.8	1.4	m	WWidthB1	1.8	1.6	m	WWidthG1L	3.0	2.2	m
LRw_LOGGIA	1.8	1.4	m	WWidthB2	1.2	1.2	m	WWidthG2L	1.2	1.2	m
PLOGGIAN	1.8	0.6	m	WWidthC1	2.4	2.0	m	WWidthG3	1.2	1.0	m
LRw_LOGGIAN	1.8	0.6	m	WWidthC2	2.7	2.7					

Table 5. Comparison of the primary energy demand for heating. cooling. DHW and ventilation between the initial and optimized scenario.

Flat	€heat/m^2	Savings(%)	€cool/m^2	Savings(%)	€water/m^2	€VMC/m^2	€tot/m^2	Savings(%)	Energy rating
A (Ini)	4.27		1.26		1.58	1.24	8.35		A1
A (Opt)	**2.87**	-33%	0.70	-44%	1.58	1.24	**6.39**	-23%	A2
B (Ini)	2.85		1.52		1.80	1.24	7.41		A1
B (opt)	1.79	-37%	0.82	-46%	1.80	1.24	5.65	-24%	A2
C (Ini)	3.10		0.82		1.62	1.24	6.78		A1
C (Opt)	1.97	-36%	**0.68**	-17%	1.62	1.24	5.51	-19%	A2
D (Ini)	3.04		0.80		1.62	1.24	6.70		A1
D (Opt)	1.95	-36%	**0.68**	-15%	1.62	1.24	5.49	-18%	A2
E (Ini)	2.50		1.72		1.82	1.24	7.28		A1
E (Opt)	1.67	-33%	0.95	-45%	1.82	1.24	5.68	-22%	A2
F (Ini)	2.20		1.68		1.82	1.24	6.94		A1
F (Opt)	**1.31**	-40%	**1.03**	-39%	1.82	1.24	**5.40**	-22%	A2
G (Ini)	4.34		1.18		1.60	1.24	8.36		A1
G (Opt)	2.75	-37%	0.78	-34%	1.60	1.24	6.37	-24%	A2
Floor	3.34		1.22		1.66	1.24	7.46		A1
Floor (Opt)	2.15	-36%	0.80	-34%	1.66	1.24	5.85	-22%	A2

As shown in Table 4, the thermal resistance of the wall insulation is equal to the maximum parameter value (Table 2), which corresponds to a U-value equal to 0.15 W/m^2K. The solar absorption coefficient, for North West and East orientations, is higher than the one of initial scenario. The selected window type for South orientation, is WT7, characterized by low thermal transmittance (U_w=0.94 W/m^2K) and high solar factor (g=0.50) with reduced shadings, for maximizing the solar gains in winter. In general, the optimization process tends to select windows equal or smaller than those of initial scenario as well as reduced depth of the loggias facing both North and South.

In the optimal scenario, the thermal performance of the building envelope is very close to the passive standard guidelines that suggest U-values not exceeding 0.15 W/m^2K for opaque building components, 0.80 W/m^2K for windows and g-value of at least 50%. Those values are lower than those set for the reference building by the actual Italian legislation, which, in climatic zone E, are equal to 0.26 W/m^2K for opaque walls and 1.40 W/m^2K for windows (minimum requirements at 2019/2021). As shown in Table 5, those flats with higher S/V, South exposure and higher energy costs in the initial scenario take more advantage of the technical and performance improvements selected by the optimization process reducing their operational cost by the greatest amount. Also in the optimal scenario, the highest energy cost for heating was calculated for flats A and G (respectively 2.87 €/m^2 and 2.75 €/m^2), the lowest for flat F (1.31 €/m^2). Flats C and D present the lowest energy cost for cooling (0.68 €/m^2) followed by flat A and G. The optimization process leads to reduce the annual energy cost by 33%-40% for heating and by 15%-46% for cooling. Considering also the other energy uses (ventilation fans and DHW) the total operational cost savings vary from 18% to 24%, leading to improving the energy rating of each flat, passing from A1 to A2. Due to the lower incidence of heating and cooling needs on the total energy demand, the differences in costs between the flats are reduced in the optimal scenario, ranging from 6.39 €/m^2 for flat A to 5.40 €/m^2 for flat F.

5. Conclusion

The analyzed building is a typical case in the design of multi-family buildings for social housing in Italy. Results show that the optimization procedure allows to obtain significant benefits in terms of operational costs. In fact, the optimization process allowed evaluating thousands of different building configurations leading the optimal solution to reduce the operational costs by 35%-40% for heating and by 15%-46% for cooling. Considering also the remaining energy uses (DHW and ventilation fans) the optimal scenario reduces the total operational costs by around 20% with respect to initial scenario. These means that the adopted optimization process allowed a reduction of heating and cooling demand, lowering the incidence of these energy uses on the total operational costs of the case study floor. For this reason, in the optimal scenario, the differences in the specific energy costs of each flat tend to be equalized. The energy rating of the floor and of each flat jumps from class A1 to class A2. This outcome is significant because it allows reducing differences in the energy consumption, and therefore in the operational costs, between different flats within the same multi-family building.

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