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

Maria Ferrara[a], Elisa Sirombo[a]*, Alberto Monti[a], Enrico Fabrizio[a], Marco Filippi[a]

[a]*DENERG, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy*

Abstract

In Europe, the recast of the Directive on the Energy Performance of Building and the consequent Zero Energy Buildings objective that has to be reached for all new buildings by 2020, lead designers to re-think building design as a complex optimization problem aimed at identifying the most effective strategies to improve building performance. These strategies can help reducing not only the climate change effect, but also the risk of energy poverty for low-income households.

This work is intended to apply a simulation-based optimization methodology for optimizing the energy performance of a multi-family building for social housing. The method combines the use of TRNSYS® with GenOpt®. A typical floor of a real case study was modeled and the impacts of the variation of several design parameters on the heating and cooling demand were assessed. The optimization lead to reduce the primary energy demand of a floor by 36%. The resulted differences in performance and energy rating between flats were analyzed.

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

1. Introduction

In Europe, the adoption of the recast of the Directive on the Energy Performance of Building [1] pushed Member States to establish new regulations with new minimum energy performance requirements. In the residential sector, improving the energy efficiency of new and existing multi-family buildings also constitutes a challenge for working

* Corresponding author. Tel.: +39-011- 090-4552.
E-mail address: elisa.sirombo@polito.com

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against the risk of energy poverty for low-income households. In fact, it has been proved that financial problems may oblige people to consume less energy, leading to the incomplete satisfaction of their needs [2]. As reported in [3], 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 a deeper economic problem like Portugal, Slovakia and Ireland the corresponding decrease was 16%, 22% and 22% respectively. A recent study in Italy, estimates that between 5% and 20% of households was in energy poverty in 2012 [4].
Associated to this problem, it is important to consider also one of the possible effects of the climate change that may contribute in reducing heating needs, but increasing the summer cooling requirements of buildings. Within a more comprehensive approach towards the implementation of economic sustainability principles, 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. 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 [5].

1.1. Scope of the work

The aim of the work is to apply a simulation-based optimization methodology, defined in [6] for a detached house and in [7] for a school classroom, to assess the potential reduction of the primary energy demand 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 primary energy demand for heating and cooling of each flat. With the addition of the primary energy demand for DHW and ventilation fans, the work also evaluates the potential reduction of the primary energy demand for heating, cooling, DHW and ventilation fans (that will be named as “total” hereinafter) due to the optimization process. Lighting is not considered according to the Italian legislation on energy rating of residential building.

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 U-value equal to 0.26 W/m^2K. Transparent surfaces are double low-e glass windows with metal frame, having U-value equal to 1.45 W/m^2K and a solar factor equal to 0.59. Some windows are shaded by external loggias, a typical feature of the Italian architecture.

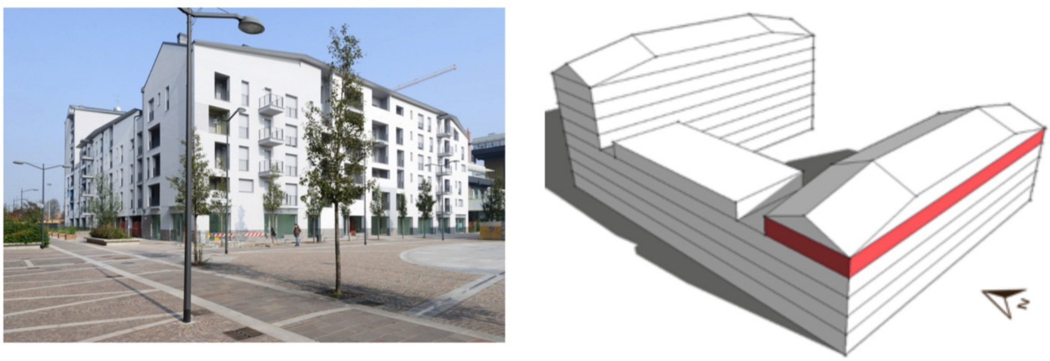

Fig. 1. The multi-family building, in red is the case study floor.

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 heating exchanger 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 m^{-1} of "A" to 0.26 m^{-1} of "C" and "D". "E" and "F" are the only units to present only South-oriented external surfaces.

Fig. 2. Case study floor plan.

Considering the actual scenario (initial scenario) the primary energy demand for heating, cooling, DHW and ventilation fans was calculated for each flat of the case study floor. 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, 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). Hot water and ventilation fans energy needs 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 holiday periods were considered. The ventilation rate was set equal to 0.7 ach.

Table 1. Primary energy demand for the different uses (Initial scenario). In bold type the min and max values.

Zone	Su (m^2)	S/V (m^{-1})	EP_H (kWh/m^2a)	EP_C (kWh/m^2a)	EP_W (kWh/m^2a)	EP_V (kWh/m2a)	EP_{gl} (kWh/m^2a)	Energy rating
A	86.0	**0.74**	26.5	15.3	21.9	15.1	**78.8**	A1
B	48.7	0.66	17.7	18.3	25.0	15.1	76.1	A1
C	77.5	**0.26**	19.2	10.0	22.4	15.1	66.7	A1
D	77.5	**0.26**	18.9	**9.7**	22.4	15.1	**66.0**	A1
E	47.4	0.32	15.5	20.7	25.2	15.1	76.5	A1
F	47.6	0.27	**13.6**	**20.2**	25.1	15.1	74.2	A1
G	81.1	0.45	**26.9**	14.4	22.2	15.1	78.6	A1
Tot. floor	465.8	0.46	20.7	14.7	23.1	15.1	73.6	A1

Table 1 shows the results of the energy performance calculations of the flats of the case study floor.

Energy ratings were calculated according to the Italian regulation (DM 26/06/2015) that introduced new methods for evaluating and rating the building energy performance. Although the energy rating of each flat is the same (class A1), the specific primary energy demand varies significantly, ranging from 78.8 kWh/m^{2}y for flat A to 66.0 kWh/m^{2}y for flat D. This is mainly due to the variation in the specific primary energy demand for heating (EP_H) and cooling (EP_C). The highest energy need for heating was calculated for flats A and G, the ones with the highest surface to volume ratio. Other units' surface/volume ratios are lower than those of flats A and G with EP_H reduction of about 30% for flats C and D (EP_H equal to 15.5 kWh/m^{2}y for flat E and 13.6 kWh/m^{2}y for flat F).

Flats C and D present the lowest primary energy demand for cooling since the large part of the internal zones are facing North and loggias on the South provide efficient solar shading. For flats E and F, EP_C is almost double.

3. Method

The work was performed according to the following steps:

- Definition of the design parameters;
- Implementation of sensitivity analysis to evaluate the influence of the design parameters on the energy need for heating and cooling of the total floor case study;
- Implementation of optimization process to evaluate the potential reduction of the primary energy demand for heating and cooling of each flat of the floor case study, considering the interrelation between the defined design parameters.
- Analysis of the effect of the optimization process on the total primary energy demand of each flat.

3.1. Design parameters

As presented in Tables 2-3 and Figs. 2-3, 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.

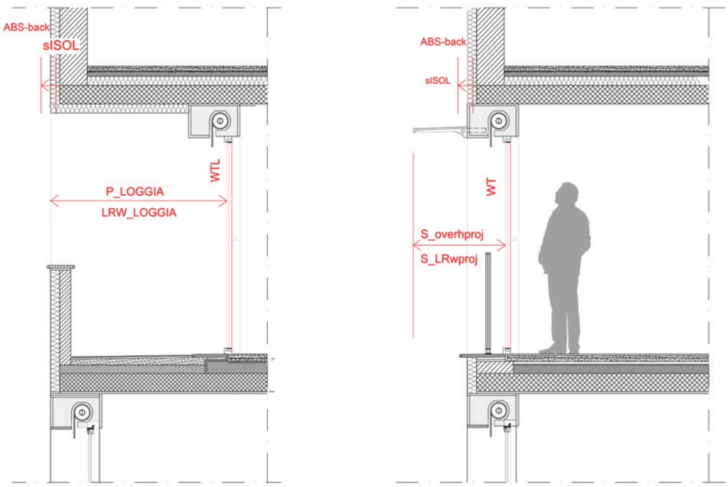

Fig. 3. Representation of the envelope design variables defined as optimization parameters.

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^2K/W	1.12	5.4	0.61	1.73
sISOLEW	East/West walls - thermal resistance of the insulation layer	m^2K/W	1.12	5.4	0.61	1.73
sISOLS	South walls - thermal resistance of the insulation layer	m^2K/W	1.12	5.4	0.61	1.73
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
PLOGGIAS	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/m^2K)	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. Parametric analysis

After the parameter definition, a parametric analysis was performed [8], in order to study the impact of the variation of each design variable on the heating and cooling energy needs of the case study.

Through the coupling of TRNSYS® and the Genopt® optimization program, the heating and cooling objective functions can be calculated by TRNSYS [9] using as input the parameter values selected by GenOpt [10]. In an iterative input-output process, the parametric algorithm of GenOpt varies the value of one parameter at a time from its minimum to its maximum value with a discrete variation step, while the others are fixed to their initial value, and TRNSYS calculates the heating and cooling energy needs for each building configuration. In Table 2, the minimum and the maximum values, as well as the variation step and the initial value are reported for all parameters.
The initial value of each parameter was fixed equal to that corresponding to the actual configuration of the case study building, so that the parametric analysis was able to quantify the differences in terms of cooling and energy needs that may occur on the current case study building when a design parameter is varied.

3.3. Optimization process

The sensitivity analysis allows assessing which are and to what extent the parameters can be varied for improving the energy performance of the case study building in its current configuration. However, it has to be noted that, as all design variables are interrelated, the impact of the variation of one parameter on the final energy demand depends on the values of other parameters. Therefore, in order to minimize the energy needs of the case study building, it is necessary to vary all the design variables together.

Since the objective is to minimize the total energy need, the heating and cooling needs (respectively Q_H and Q_C) were summed up in terms of primary energy (PE_{H+C}). Therefore, based on the efficiencies and the primary energy conversion factors of the energy system considered for the case study building (Par. 2), the objective function for the optimization was set as

$$PE_{H+C} = \frac{Q_H}{\eta_H} \cdot f_H + \frac{Q_C}{EER} \cdot f_C = \frac{Q_H}{0.88} \cdot 0.62 + \frac{Q_C}{2.05} \cdot 2.42 \quad (1)$$

The optimization process was performed through the previously described 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.

The optimization process was run two times: a first time to minimize the objective function, a second time to maximize 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 energy performance of the real building design and the potential optimal configuration.

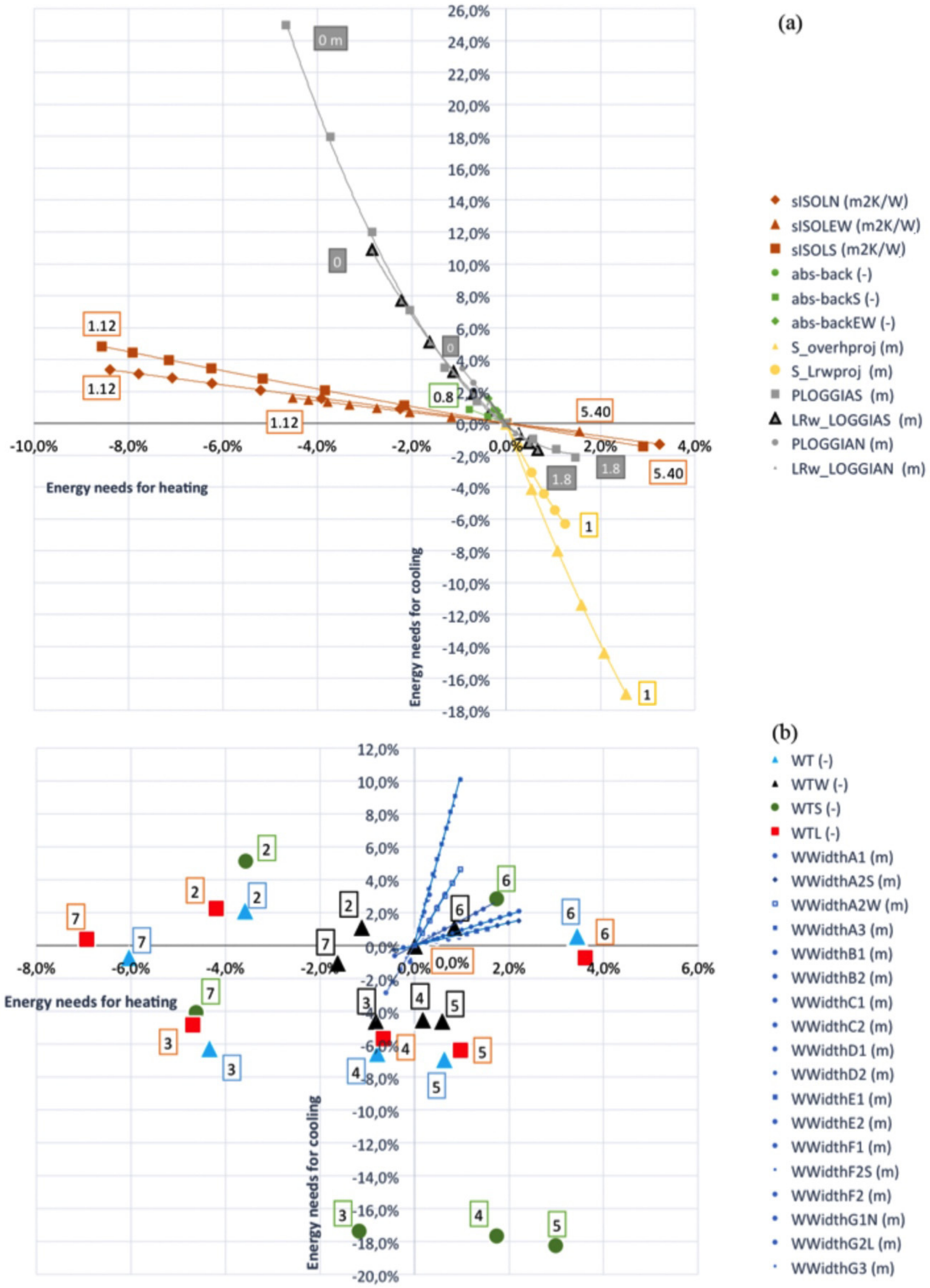

Fig. 4. Results of the parametric analysis. Effect of the opaque (a) and transparent (b) envelope design in the heating and cooling needs .

4. Results

4.1. Parametric analysis

The results of the parametric analysis are shown in Fig.4. Each curve represents the variation of the heating and cooling demand of the total floor as a function of the variation of a specific design parameter. The initial scenario corresponds to the 0% point, where all the parameters are set to their initial values.

The variation within the range of all the design parameters related to the opaque envelope has opposite effects on the heating and cooling demand of the total floor. The increase of the thickness of the wall thermal insulation decreases the heating demand by 8% and increases the cooling demand up to 5%. Moreover, if the effect of the solar absorption coefficient of the external wall is marginal for all the orientation, the design of the solar shading systems is crucial for the South orientation. The reduction of the depth of the loggias facing South corresponds to lower heating demands, due to exploitation of solar gains, but generates higher energy cooling demand, up to 25%.

Concerning parameters relate to the transparent envelope, for South and North orientations, some windows types reduce the energy demand for both heating and cooling by about 4%-6% (WT3, WT7 only for South orientation). Moreover, respect to the initial scenario, for North, West and loggia windows, the window types characterized by lower U-value and equivalent g factor (WT7) causes a reduction of the heating demand without affecting significantly the cooling demand. The opposite effect is registered for window types characterized by similar U-value but lower g factor (WT5). WT6 has negative effects on all the orientation. In general, the effect of the variations on the west orientation is less significant because of the small transparent area, whereas on the South orientation, for window without solar shadings, the variation of results is remarkable (variation in the range -4,6% - +3% for heating energy demand and -18,2% - +5,1% for cooling energy demand). Concerning the width of the windows, for all the orientation, the increase of transparent area leads to increasing the heating and cooling demand.

In general, the sensitivity analysis allows determining which are the most influent design parameters on the annual energy demand. These are, in the case study, the followings: the thermal resistance of the opaque envelope, the characterization of the solar shading systems for South orientation and the window types.

4.2. Optimization process

Results related to the optimization of the case study are shown in Fig.5. All the objective function values, each related to one of the around 7000 different building configurations analyzed, were ordered from the maximum (MAX PE_tot) to the minimum (MIN PE_tot) value. The highest possible increase and decrease of the different energy demands with respect to the initial configuration (INI) are reported.

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

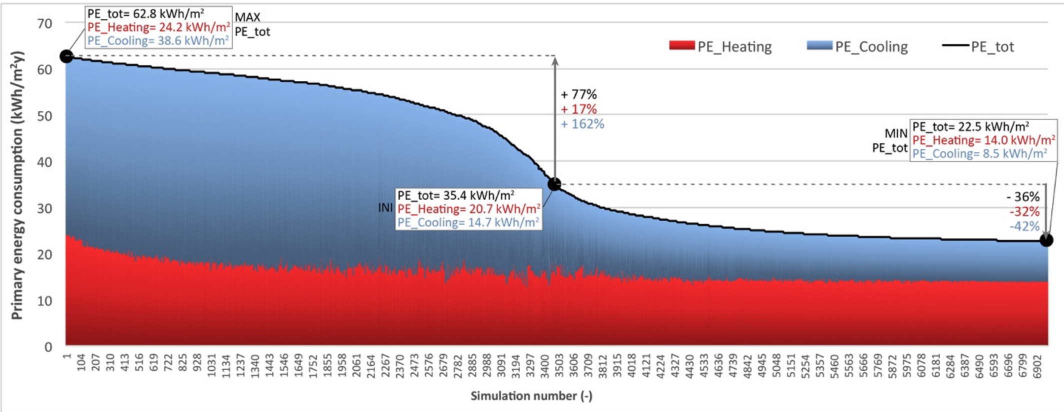

Fig. 5. Results of the optimization process.

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	1.73	5.40	m^2K/W	WT	1	3	-	WWidthD1	2.4	2.0	m
sISOLEW	1.73	5.40	m^2K/W	WTS	1	3	-	WWidthD2	2.7	2.7	m
sISOLS	1.73	5.40	m^2K/W	WTW	1	3	-	WWidthE1	1.2	1.2	m
abs-back	0.2	0.2	-	WTL	1	3	-	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	0.2	-	WWidthA2W	0.9	0.9	m	WWidthF2S	0.9	0.9	m
S_overhproj	0	0.8	m	WWidthA2S	1.2	0.8	m	WWidthF2	1.8	1.6	m
S_LRwproj	0	0.8	m	WWidthA3	1.8	1.8	m	WWidthG1N	0.9	0.9	m
PLOGGIA	1.8	1.8	m	WWidthB1	1.8	1.6	m	WWidthG1L	3.0	2.2	m
LRw_LOGGIA	1.8	1.8	m	WWidthB2	1.2	1.2	m	WWidthG2L	1.2	1.2	m
PLOGGIAN	1.8	1.8	m	WWidthC1	2.4	2.0	m	WWidthG3	1.2	1.0	m
LRw_LOGGIAN	1.8	1.8	m	WWidthC2	2.7	2.7					

Table 5. Comparison heating, cooling, DHW and ventilation energy demands between the initial and optimized scenario.

Flat	EP_H (kWh/m^2y)	Energy Saving (%)	EP_C (kWh/m^2y)	Energy Saving(%)	EP_W (kWh/m^2y)	EP_V (kWh/m2y)	EP_{gl} (kWh/m^2y)	Total Primary Energy Saving (%)	Energy rating
A (Ini)	26.5		15.3		21.9	15.1	78.8		A1
A (Opt)	17.8	-33%	7.7	-50%	21.9	15.1	62.5	-21%	A2
B (Ini)	17.7		18.3		25.0	15.1	76.1		A1
B (Opt)	12.3	-31%	9.0	-51%	25.0	15.1	61.5	-19%	A2
C (Ini)	19.2		10.0		22.4	15.1	66.7		A1
C (Opt)	12.9	-33%	**7.6**	-24%	22.4	15.1	58.1	-13%	A2
D (Ini)	18.9		9.7		22.4	15.1	66.0		A1
D (Opt)	12.9	-32%	**7.6**	-22%	22.4	15.1	**58.0**	-12%	A2
E (Ini)	15.5		20.7		25.2	15.1	76.5		A1
E (Opt)	11.5	-26%	10.4	-50%	25.2	15.1	62.2	-19%	A2
F (Ini)	13.6		20.2	-	25.1	15.1	74.2		A1
F (Opt)	**9.0**	-34%	**11.4**	44%	25.1	15.1	60.7	-18%	A2
G (Ini)	26.9		14.4		22.2	15.1	78.6		A1
G (Opt)	**17.9**	-33%	8.8	-39%	22.2	15.1	**63.9**	-19%	A2
Floor (Ini)	20.7		14.7		23.1	15.1	73.6		A1
Floor (Opt)	14.0	-32%	8.5	-42%	23.1	15.1	60.7	-18.0%	A2

As shown in Table 4, the thermal resistance of the insulation panel of the exterior walls is equal to the maximum parameter value (Table 2), corresponding to a U-value of the opaque wall equal to 0.15 W/m^2K. For all the orientation, the selected window type is the WT3, which is characterized by lower thermal transmittance ($Ug = 0.7W/m^2K$) and solar factor g (g=0.29), in combination with horizontal overhangs and vertical fins 0.8 m deep only for windows facing South. Coherently with the results of the parametric analysis, WT3 allows the better annual balance between the heat loss and the solar heat gains reduction. For some parameters, such as the solar absorption coefficient of the external walls, the depth of the loggia and the width of some windows, the optimal value corresponds to the initial one. In general, the optimization process tends to select windows equal or smaller than those considered in the initial scenario. As shown in Fig. 5, the optimal solution decreases the heating energy demand, because of the increase in the thermal insulation of the building envelope (opaque and transparent). However, it is clear that the optimization process is driven by cooling needs and therefore tends to optimize the summer performance of the building, selecting strategies that reduce the solar heat gains in summer (low g-value, solar shading devices, smaller window). As shown in Table 5, those flats with higher S/V, South exposure and higher primary energy demand in the initial scenario take more advantage of the technical and performance improvements selected by the optimization process improving significantly their energy performance.

Also in the optimal scenario, the highest energy need for heating was calculated for flats A and G (EP_H respectively equal to 17.8 and 17.9 kWh/m^{2}y), the lowest for flat F (EP_H equal to 9.0 kWh/m^{2}y). Flats C and D present the lowest primary energy demand for cooling (EP_C equal to 7.6 kWh/m^{2}y) followed by flat A. For flats E and F, EP_C is a 50% higher. The optimization process leads to reduce the primary energy demand by 26%-33% for heating and by 22%-51% for cooling. Considering the remaining energy uses, fans ventilation and DHW, the total primary energy savings vary from 12% to 21% allowing an improvement of the energy rating of each flat, passing from A1 to A2. Due to the lower incidence of heating and cooling needs on the total primary energy demand, the variation between each other of the specific primary energy demand of flats is lower in the optimal scenario, ranging from 63.9 kWh/m^{2}y for flat G to 58.0 kWh/m^{2}y for flat D.

5. Discussion

The optimization process allowed evaluating thousands of different building configurations leading the optimal solution to reduce the primary energy demand for heating by 26%-33% and the one by 22%-51% for cooling. Considering also the remaining energy uses (DHW and ventilation fans) the optimal scenario reduces the total primary energy consumption by around 20% with respect to initial scenario. This means that the adopted optimization process allowed a reduction of heating and cooling demand, lowering the incidence of these energy uses on the total energy demand of the case study floor. So that, in the optimal scenario, the differences in the specific primary energy demand, and therefore in the operational cost, between each flat tend to be minimized.

Beyond the numerical results, the study demonstrated that a good design can only result from the simultaneous optimization of the many involved design variables and proposed a simulation tool and a methodology for addressing this optimization problem. Further study will focus on the results of an optimization based on the minimization of operational costs.

6. Conclusion

The analyzed building is a typical case in the design of multi-family buildings for social housing in Italy. The design of such buildings is often oriented to the reduction of the energy need for heating. However, results show that it is possible to obtain significant benefits in the reduction of the total energy consumption taking into account both heating and cooling demand. Moreover, the energy rating of the floor and of each flat improves from class A1 to class A2. Since energy labels are gradually receiving positive responses and recognition from the market, this outcome is also significant.

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