The impact of thermal comfort in multi-objective optimization of buildings refurbishment

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Abstract

The European Committee is encouraging the Member States to adopt the so-called "cost optimal approach" to define new energy performance requirements for new and existing buildings. However, the cost-optimal should not neglect the indoor thermal comfort. The improvement of the building energy performance, especially if related to the addition of high insulation thickness, can increase the risk of overheating. A small energy input raises the internal temperature considerably. Therefore, in order to move beyond the mere economic optimization of retrofit interventions, it is important to understand what the solutions able to enhance the performance of the buildings are, also in terms of thermal comfort. In this paper, this problem has been investigated. The analysis has been carried out on a set of different residential building modules, representative of different building typologies and construction periods, located in two different climatic contexts. By means of a multi-objective optimization approach, the best combination of EEMs has been defined first optimizing only the energy and economic aspects, then the indoor thermal comfort has been added and the optimization re-run. A Genetic Algorithm (NSGA-II) coupled with a simulation tool has been used to optimize the different objectives.

1. Introduction

Designing the energy refurbishment of existing buildings is not an easy task. Firstly, the wide selection of Energy Efficiency Measures (EEMs) currently available on the market has to be evaluated. Then, the choice among EEMs has to be made considering the objectives to be reached. The European Commission promotes the improvement of the energy performance of the existing building stock, through the so-called "cost optimal approach" in the definition of new energy performance requirements. Even though the Delegated Regulation 244/2012 suggests that the selected EEMs shall be compatible with air quality and indoor comfort levels, according to EN 15251 (CEN, 2007a), the cost-optimal approach does not include this important aspect in the optimization process. As highlighted by the EPBD recast (EU, 2010), retrofit strategies should enhance the thermal comfort of the buildings, limiting the employment of air conditioning system. The overheating issue, connected to high performance buildings, has been already pointed out in the literature (Mlakar J. et al., 2011; McLeord R.S. et al., 2013; Penna P. et al., 2014). For this reason, it is important to understand what solutions are able to enhance the performance of the buildings, also in terms of comfort, to move beyond the mere economic optimization of retrofit interventions.

In this paper, the effect of thermal comfort in defining the optimal EEMs has been investigated. The analysis has been conducted on a set of different residential building modules, representative of different building typologies and construction periods, located in two different climatic contexts. Conventional retrofit measures, such as the insulation of the external envelope, substitution of glazing system, replacement of the boiler and addition of a mechanical ventilation system have been analysed. A multi-objective optimization approach has been repeated, firstly to define the combination of EEMs able to minimize energy consumptions and costs, then also the indoor thermal discomfort. A genetic algorithm

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(NSGA-II) coupled with the simulation code TRNSYS (Solar Energy Laboratory, 2012) has been used.

2. Building modules description

A single storey residential unit with a floor area of 100 m^2 and an internal height of 3 m has been considered as the reference building module. The vertical walls are oriented towards the main cardinal points, with window surface equal to 14.4 m^2 on a single side. The window system is a single pane glass (U_{gl}=5.7 W m^{-2} K^{-1}) with a standard timber frame (U_{fr}=3.2 W m^{-2} K^{-1}). The thermal bridges have a linear transmittance of 0.098 W m^{-1} K^{-1} for corners, 0.182 W m^{-1} K^{-1} for the intermediate floor and walls and 0.060 W m^{-1} K^{-1} for the windows' perimeter, calculated according to EN 10211 (CEN, 2007b). The heating system is a standard gas boiler coupled with radiators.

Some characteristics of this shoebox-like module have been changed to create a set of residential buildings and generalize the results for different configurations, architectural typologies and construction period:

- *compactness ratio* changes to consider a detached-house-like typology (S/V=0.97 m^{-1}), a penthouse-like (S/V=0.63 m^{-1}) and an intermediate flat in a multi-storey buildings (S/V=0.3 m^{-1});
- *envelope thermal resistance* varies to consider two construction periods, before the first Italian energy legislation, (Italian Parliament, 1976), REF 1 (R_1= 0.97 m^2 K W^{-1}), and between the first and the second energy legislations (1976÷1991) (Italian Parliament, 1991), REF 2 (R_2 = 2.04 m^2 K W^{-1});
- *window orientation:* South and East.

A set of 8 shoebox-like buildings were obtained by combining the above variations. Those buildings are evaluated in two different climatic contexts: Milano and Messina, representative for northern and southern Italy.

The infiltration rate and the nominal power of the heating system change according to the reference building module. The reference air tightness n_{50} is 7 ACH and the associated infiltration rates, calculated according to the EN 12207 (CEN, 1999) and EN 15242 (CEN, 2007c), change depending on the compactness ratio (Table 1). The nominal heating power has been calculated for each reference case according to the EN 12831 (CEN, 2003) and the boiler nominal capacity has been selected from market available products.

Table 1 – Infiltration rate values (ACH) according to different compactness ratios

S/V=0.3	**S/V=0.63**	**S/V=0.97**
0.062	0.130	0.200

3. Retrofit Strategies

The following Energy Efficiency Measures have been considered to improve the performance of the building modules:

- external insulation of walls, roof and/or floor with EPS (conductivity λ=0.04 W m^{-1} K^{-1}, specific heat c=1470 J kg^{-1} K^{-1}, density ρ=40 kg m^{-3}) in a range between 1 to 20 cm, incremented by 1 cm;
- replacement of existing window systems with four higher performance glazing systems (Table 2) and improved aluminum frames with thermal break (U_{fr}=1.2 W m^{-2} K^{-1});
- substitution of heating generator with modulating or condensing boiler both with a climatic control system;
- installation of mechanical ventilation system with heat recovery (Ventilation rate q_v=150 m^3 h^{-1}, Power P=60 W).

The following listed EEMs bring energy performance improvements without extra-costs:

- the linear thermal transmittance of thermal bridges is reduced depending on the insulation thickness and on window type. By means of a finite element tool (LBNL, 2013), a polynomial regression was calculated, considering a progressive increase of 5 cm of insulation, to consider the variation of the thermal bridge effect;

- the infiltration rates are considered as half of the original value (Table 1) if the windows are replaced, because of the improvement of air tightness;
- if the boiler is substituted, the radiators' supply temperatures can be lower than the design one, because the capacity of radiators does not change and the climatic control system allows the supply temperature regulation depending on the external one.

Table 2 – Characteristics of the different glazing system

Glazing system	U ($W\ m^{-2}\ K^{-1}$)	SHGC
DH – Double, high SHGC (4/9/4, krypton, low-e)	1.140	0.608
DL – Double, low SHGC (6/16/6, krypton, low-e)	1.099	0.352
TH – Triple, high SHGC (6/12/6/12/6, krypton, low-e)	0.613	0.575
TL – Triple, low SHGC (6/14/4/14/6, argon, low-e)	0.602	0.343

4. Multi-Objective approaches

4.1 Genetic Algorithm (NSGA II)

The optimization process has been implemented through the Non-dominated Sorting Genetic Algorithm, NSGA II (Deb K. et al. 2002), coupled with the dynamic simulation tool, Trnsys. This approach is particularly useful in the problem characterized by the competing nature of the objectives. By means of the NSGA II, it is possible to find a set of optimal solutions, the so-called non dominated solutions, for which no alternatives exist that increase the fulfilment of an objective without hampering the attainment of another. The parameters set for the genetic algorithm are 0.5 as for the fraction of tournament selection without replacement (TSWOR), 0.8 as for the arithmetic crossover and a mutation rate of 0.1. Sobol's sequences sampling is used to define the 128 individuals of the initial population. This pseudo-random number generator avoids the oversampling of same region that can occur with random sampling (Saltelli A., 2004), giving a good individuals' collection as first population. A Matlab (Matlab 7.7.0 R 2008) code executes automatically the TRNSYS model of the building, evaluates the attainment of the objectives and selects the best individuals that are used as parents of the following generation. The iterative process is repeated until the maximum number of iterations or the convergence level is reached. The final population contains the optimal solutions.

4.2 Optimization 1: Energy and Costs

This NSGA II algorithm has been used to define the best combination of EEMs for the analysed reference residential modules, in a bi-optimization process. The minimization of energy consumption and costs has been pursued setting as objective functions the Energy Performance for Heating (EPH) and the Net Present Value (NPV), described in the following sections.

4.2.1 Energy performance for Heating

The Energy Performance for Heating (EP_H) is calculated through the simulation code TRNSYS v.17 (Solar Energy Laboratory, 2012). National Test Reference Years of Milano and Messina (Comitato Termotecnico Italiano, 2012) are used to consider the weather conditions. The thermo-physical properties of the building are simulated with the Type 56, multi-zone building subroutine. The heating system is modelled by means of the Type 869 (Haller M.Y. et al., 2011a; Haller M.Y. et al., 2011b), able to simulate the behavior of modulating and condensing boilers (Carlon et al., 2015). In combination with the replacement of the boiler, a climatic adjustment of the water supply temperature, controlled by an external air temperature probe, is considered. A heating thermostatic control keeps the air temperature in the range between 20 and 22°C. The occupancy schedule and the internal gains, considered half radiative and half convective, are modelled according to the Italian technical specification UNI/TS 11300 (UNI, 2008). The internal gains (Table 4) are defined on the base of the room type.

The floor area is considered half as living rooms and half as bedrooms. The air change rate, during the occupancy time, is set to 0.5 ACH. The same air change rate is set when the occupants are present in case that mechanical ventilation system is considered. In this last configuration, the outdoor inlet air is pre-heated in the heat recovery. In the summer season, the mechanical ventilation system is also operated to avoid the indoor overheating. In this case, during the occupied and not-occupied periods, whenever the operative temperature overcomes the upper limit of the comfort range (see paragraph 4.3.1) and the outside conditions can improve the internal comfort (the outside temperature is lower than the indoor one) the mechanical ventilation system turns on, bypassing the heat recovery. If the outdoor conditions are worse than those inside (too cold or too hot), the mechanical ventilation is operated with a fixed airflow rate of 0.5 ACH and with heat recovery just during the occupied periods.

4.2.2 Net Present Value

The Net Present Value (NPV) is calculated according to the comparative framework methodology of the cost-optimal level (European Committee, 2012). The NPV, considering different time series of cash flows, allows to evaluate the economic benefits associated with the possible retrofit solutions. The NPV is evaluated for a lifespan of 30 years and takes into account:

- the *initial Investment Costs (IC)*, reported in Table 5 and defined from the comparison of different regional databases (Regional Price List, RPL, of Lombardy, Lazio and Sicily);
- the annual running costs, composed of the *Annual Energy Cost (EC)* and the *Maintenance Cost (MC)*. The EC has been calculated considering the fuel and electricity price rising (Table 4);
- the *replacement cost (RC)*, for the periodic substitution of building/system elements;
- the *residual value (RV)* for the equipment with longer lifespan (CEN, 2007d).

Table 3 – Investment costs without VAT of the considered retrofit strategies

Retrofit strategies	**IC**
Vertical walls insulation	IC_W =160 x* + 38.53 [EUR m^{-2}] *insulation thickness [m]
Horizontal walls insulation	IC_H =188 x* + 8.19 [EUR m^{-2}] *insulation thickness [m]
DH – Double, high SHGC	IC_{DH} = 404.33 [EUR m^{-2}]
DL – Double, low SHGC	IC_{DL} = 439.06 [EUR m^{-2}]
TH – Triple, high SHGC	IC_{TH} = 477.65 [EUR m^{-2}]
TL – Triple, low SHGC	IC_{TL} = 454.49 [EUR m^{-2}]
Standard Boiler (STD)	IC_{STD} = 1000 [EUR]
Modulating Boiler (MD)	IC_{MDL} = 1500 [EUR]
Condensing Boiler (CD)	IC_{CND} = 2000 [EUR]
Mechanical ventilation system (MVS)	IC_{MVS} = 6000 [EUR]

Table 4 – Parameters for the definition of the Energy Costs

Fuel Cost (natural gas) (1)	0.85 [EUR Sm^{-3}]
Lower Heating Value	32.724 [MJ Sm^{-3}]
Annual rate of increase fuel price(2)	2.8%
Electricity Costs(1)	0.25 [EUR kWh_{el}^{-1}]
Annual rate of increase electricity price(2)	1.71%
Real Interest Rate(3)	3%
VAT(4)	10%

(1) Domestic customer (AEEG 2013); (2) (European Commission 2009); (3) (European Commission 2012); (4) Italian Parliament (1972)

4.3 Optimization 2: Energy, Costs and Comfort

A second Optimization has been run, considering the thermal comfort as the third objective. In this case the best combination of EEMs are defined to minimize the Energy Performance for Heating (EPH), the Net Present Value (NPV) and the Weighted Discomfort Time (WDT).

4.3.1 Weighted Discomfort Time (WDT)

The WDT is calculated according to the Annex F of the EN 15251 (CEN, 2007a), through the Degree Hours Criteria. This index weights the occupied hours, during which the actual operative temperature lies outside the comfort range, by a weighting factor that depends on the entity of the deviation (Equation 1 and 2).

$$WDT = \Sigma\ wf \cdot time \qquad (1)$$

$$wf = \Theta_0 - \Theta_{0,limit}$$
$$\text{when } \Theta_0 < \Theta_{0,limit,lower} \text{ or } \Theta_0 > \Theta_{0,limit,upper} \qquad (2)$$

The comfort range is defined on the basis of a normal level of expectation (Category II) for an activity level of 1.2 met and a clothing index of 1 clo. The lower and upper limits vary according to the heating and non-heating season. During the heating season, defined pursuant to the Italian legislation (Italian Parliament, 2013), the lower and upper values for the operative temperature are fixed, i.e. 20°C and 25°C. During the rest of the year, the comfort range is set according to the adaptive comfort approach (passive operational mode), defined by the annex A of the EN 15251:2007, as follow (Equation 3a and 3b):

$$\Theta_{o,limit,upper} = 0.33\ \Theta_{rm} + 18.8 + 3 \qquad (3a)$$

$$\Theta_{o,limit,lower} = 0.33\ \Theta_{rm} + 18.8 - 3 \qquad (3b)$$

Those limits consider the individual's thermal experience described by the exponentially weighted running mean of the daily outdoor mean air temperature, Θ_{ed}, calculated on the seven days immediately before the analysed one:

$$\Theta_{rm} = (1-\alpha)\cdot(\Theta_{ed-1} + \alpha\Theta_{ed-2} + \alpha^2\Theta_{ed-3} + \ldots + \alpha^6\Theta_{ed-7}) \quad (4)$$

5. Results and discussion

5.1 Comparison between Optimization 1 and 2

Figures 1 and 2 show the Pareto Front solutions obtained with the Optimization 1 and 2. The cases reported are those of REF 2 buildings, east oriented, located in Milan and in Messina. Different colors have been used to describe the comfort performance of the non-dominated solutions, identifying five different comfort ranges. Blue dots pinpoint the solutions with the best performance in terms of comfort, while, red dots the ones with the worse performance. The highest WDTs characterize the configurations with smaller compactness ratios, because of the overheating issue. In fact, for those cases, the small area of the external envelope reduces the thermal losses in winter increasing the EP_H performance, but, in summer and in intermediate seasons, it is difficult to get rid of the excess heat. Looking to the Pareto Front of Optimization 1, the most comfortable solutions generally lie in the upper side of the front: this is probably due to the adoption of mechanical ventilation that raises the NPV. Looking at the Optimization 2 the more comfortable solutions lie in the right-upper side of the graph: this means that higher comfort performance solutions have a higher NPV and a lower EP_H. Moreover, the graphs show that the Pareto fronts obtained from the Optimization 1 are located in the left-down area of the Pareto surfaces of the Optimization 2 and they are characterized by high values of WDT. This means that optimizing only the energy and cost objectives leads to reject the most comfortable solutions. Considering the thermal comfort in the optimization process does not affect the definition of the global energy and cost optima, but it allows to select a larger number of optimal configurations that are discarded if only the energy and cost perspectives are taken into account. This aspect is also highlighted by the percentage distributions of single EEMs in the Pareto front reported in Table 5.

5.2 Thermal comfort and EEMs

The non-dominated solutions of the Optimization 1 present in almost all the cases the highest insulation levels, especially in the REF 1 cases, while in the solutions of the Optimization 2 all the insulation levels appear. This is due to the competing nature of the energy, cost and comfort objectives. In the Optimization 1, reducing the thermal losses plays a crucial role in improving the EP_H performance and to reduce the energy cost item. On the other hand, considering the comfort perspective highlights the overheating issue of high insulated buildings. In those buildings, a small energy input can significantly raise the indoor temperature and, if the excess of heat is not discharged, the indoor comfort could be compromised. Another important difference between the Pareto fronts of the Optimization 1 and 2 is the presence of the windows with low SHGC: in fact, the cost-optimization does not include this retrofit action in the optimal solutions, while it is considered in Optimization 2, because of their advantage in maintaining a better indoor thermal comfort. Concerning the replacement of the boiler, this action rarely appears in the Pareto solutions of the bi-optimization for the building with 0.3 of compactness ratio, is considered in 6 to 25% of the solutions for the compactness ratio 0.63 and in the 26 to 73% of the solutions for the highest compactness ratio. The higher the heating energy need, the better the boiler performance should be.

5.3 Global optima and best comfort performance optima

Table 6 shows the comparison between the global costs and energy optima (Global Optima, GO) and the optima of the solutions belonging to the best comfort level, WDT<1000 (Comfort Optima, CO), obtained with Optimization 2. This comparison allows us to understand what the main features of the solutions able to guarantee the best comfort performance are. As previously highlighted, some of the cases are characterized by the problem of overheating and for those it is not possible to assure comfort performance with a WDT less than 1000 K h. Hence, for the cases with windows East oriented, REF 1, 0.3 and 0.63 and REF 2, 0.3 located in Milan, the optima solutions of the best comfort performance refers to cases with a WDT less than 2000 K h even though bigger than 1000 K h.

Concerning the cost optimality, it is possible to see that for some cases (REF 1, East, 0.3 and REF 2, South, 0.3 located in Messina and REF 2, East, 0.3 located in Milan) the cost-optimal solutions of the best comfort level coincide with the reference cases. This means that for those configurations it is not possible to improve the comfort performance in a cost effective way. The configurations of cost and energy optima of the first comfort level are mainly characterized by a smaller insulation thickness and a lower windows' SHGC. Especially for the cases with smaller compactness ratio, the insulation on the external walls is often not considered.

Mechanical Ventilation should enhance the energy performance preserving the indoor comfort.

Table 5 – Percentage distribution of the EEMs for cases REF1.

REF 1									
		0.3							
		EAST				SOUTH			
		MI		ME		MI		ME	
		OPTI 1	OPTI 2	OPTI 1	OPTI 2	OPTI 1	OPTI 2	OPTI 1	OPTI 2
WALLS	0-5 cm	0%	43%	0%	43%	0%	39%	2%	45%
	5-10 cm	0%	28%	18%	28%	8%	28%	25%	30%
	10-15 cm	20%	16%	39%	16%	27%	21%	42%	19%
	15-20 cm	80%	14%	44%	14%	65%	13%	31%	6%
WINDOWS	S	0%	0%	0%	36%	0%	23%	34%	44%
	DH	58%	17%	73%	13%	69%	24%	66%	18%
	SL	0%	24%	0%	17%	0%	16%	0%	18%
	TH	38%	16%	25%	21%	31%	16%	0%	14%
	TL	4%	44%	2%	14%	0%	22%	0%	7%
BOILER	STND	96%	56%	91%	49%	95%	57%	96%	61%
	MD	4%	31%	9%	34%	5%	35%	4%	33%
	CD	0%	13%	0%	17%	0%	7%	0%	5%
VENT	NAT	68%	66%	98%	75%	68%	68%	100%	75%
	MVS	32%	34%	2%	25%	32%	32%	0%	25%
		0.63							
		EAST				SOUTH			
		MI		ME		MI		ME	
		OPTI 1	OPTI 2	OPTI 1	OPTI 2	OPTI 1	OPTI 2	OPTI 1	OPTI 2
WALLS	0-5 cm	0%	47%	0%	42%	0%	35%	0%	50%
	5-10 cm	0%	18%	0%	21%	0%	27%	10%	21%
	10-15 cm	0%	17%	34%	25%	6%	20%	41%	16%
	15-20 cm	100%	19%	66%	13%	94%	18%	49%	15%
ROOF	0-5 cm	0%	19%	0%	1%	0%	4%	0%	2%
	5-10 cm	0%	25%	15%	29%	0%	35%	24%	22%
	10-15 cm	16%	26%	35%	38%	17%	39%	54%	50%
	15-20 cm	84%	30%	50%	32%	83%	22%	22%	27%
WINDOWS	S	0%	0%	0%	19%	0%	19%	24%	39%
	DH	56%	20%	77%	42%	67%	32%	57%	25%
	SL	0%	45%	0%	21%	0%	24%	0%	23%
	TH	44%	23%	23%	8%	33%	18%	19%	15%
	TL	0%	13%	0%	10%	0%	7%	0%	0%
BOILER	STND	75%	40%	89%	70%	94%	66%	83%	57%
	MD	8%	45%	7%	21%	6%	28%	10%	32%
	CD	17%	16%	4%	9%	0%	6%	6%	11%
VENT	NAT	64%	63%	56%	74%	35%	70%	80%	74%
	MVS	36%	38%	44%	26%	65%	30%	20%	27%
		0.97							
		EAST				SOUTH			
		MI		ME		MI		ME	
		OPTI 1	OPTI 2	OPTI 1	OPTI 2	OPTI 1	OPTI 2	OPTI 1	OPTI 2
WALLS	0-5 cm	0%	36%	0%	33%	0%	34%	0%	33%
	5-10 cm	0%	25%	0%	22%	0%	26%	0%	22%
	10-15 cm	4%	22%	31%	25%	0%	24%	43%	26%
	15-20 cm	96%	17%	69%	20%	100%	16%	57%	19%
ROOF	0-5 cm	0%	0%	0%	0%	0%	0%	0%	1%
	5-10 cm	0%	0%	8%	13%	0%	4%	10%	4%
	10-15 cm	15%	64%	43%	44%	6%	61%	47%	36%
	15-20 cm	85%	36%	49%	44%	94%	34%	43%	58%
FLOOR	0-5 cm	0%	36%	0%	18%	0%	33%	0%	3%
	5-10 cm	0%	22%	4%	35%	0%	26%	4%	18%
	10-15 cm	24%	25%	51%	21%	10%	24%	49%	45%
	15-20 cm	76%	17%	45%	26%	90%	17%	47%	34%
WINDOWS	S	0%	0%	0%	18%	0%	8%	16%	18%
	DH	94%	25%	78%	26%	86%	25%	73%	35%
	SL	0%	50%	0%	31%	0%	20%	0%	20%
	TH	6%	15%	22%	22%	14%	19%	11%	14%
	TL	0%	10%	0%	3%	0%	28%	0%	14%
BOILER	STND	27%	6%	59%	43%	41%	20%	74%	45%
	MD	17%	10%	33%	43%	33%	36%	20%	38%
	CD	56%	83%	7%	15%	26%	44%	6%	18%
VENT	NAT	55%	64%	64%	66%	67%	59%	70%	69%
	MVS	45%	36%	36%	34%	33%	41%	30%	31%

Nevertheless, this solution does not appear in the CO cost-optimal solutions (except for the cases REF 1 and 2, 0.3, South and REF 2, 0.63, East located in Milan) because of the high initial investment costs. In table 6 the energy performance of the GO and CO solutions have been compared to the reference case without retrofits: the percentage difference between the EP_H, the NPV and WDT of energy and comfort optima are reported. The red negative values mean a worse indicator than the reference case. In almost all the cases, the building energy consumptions are reduced. However, the GO solutions present higher performance in terms of energy savings, with a greater economic effectiveness. Setting the best comfort level leads to solutions less effective in terms of energy and costs, but the difference between the comfort of the GO solutions is very relevant. This could compromise the effectiveness of the refurbishment, deteriorating the indoor comfort.

6. Conclusion

Comparing the results found with the cost-optimal approach and the ones in which also the thermal comfort performance is optimized, it was possible to highlight the effect of the comfort performance on the definition of the optimal retrofit solutions. The results of the cost-optimal approach show that optimizing only the energy and costs leads to rejecting the most comfortable measures, such as windows, with low SHGC or smaller insulation level. On the other hand, adding the thermal comfort as an objective function allows us to select a larger number of optimal configurations that are discarded because of the higher NPV. The most energy and cost effective measures alone generally lead to uncomfortable conditions if no other strategies are considered. Considering that the above results depended only on the envelope and systems performance, renovated buildings are likely to require a more careful operation management to avoid the overheating issue. Whether this role is played by the manual intervention of somehow trained occupants, or by some building automation technologies, the control strategies are of crucial importance in building renovation. Further developments should investigate the potential of building management strategies also based on automated systems to maintain adequate comfort condition while reducing the energy demand.

Table 6 - Global Optima (GO) and Comfort Optima (CO) for cases REF 1-2, 0.3-0.97, South oriented, located in Milan and Messina.

	REF 1							
	0.3				0.97			
	MI		ME		MI		ME	
	GO	CO	GO	CO	GO	CO	GO	CO
	COST OPTIMAL							
Wall	12	0	11	5	15	10	12	12
Roof	-	-	-	-	14	15	11	11
Floor	-	-	-	-	15	8	10	10
Wind	DH	DL	0	0	DH	0	0	0
Boiler	STD	STD	STD	STD	STD	MD	STD	STD
Vent	STD	MVS	STD	STD	STD	STD	STD	STD
EPH	8	41	13	19	43	87	35	35
NPV	14	32	9	10	32	37	21	21
WDT	6337	855	1270.3	951	2466	977	542	542
% EPH	92	59	68	51	76	51	71	71
% NPV	49	-16	22	12	35	24	36	36
% WDT	-519	16	-136	-77	-161	-3	38	38
	ENERGY OPTIMAL							
Wall	17	0	18	3	19	9	18	17
Roof	-	-	-	-	18	15	20	20
Floor	-	-	-	-	19	9	18	12
Wind	TH	DL	DH	DL	TH	TL	TH	TL
Boiler	STD	STD	STD	MD	CD	CD	CD	CD
Vent	MVS	MVS	STD	MVS	MVS	MVS	MVS	MVS
EPH	0.493	41	0.3	1	12.84	39	0.6	3
NPV	27.45	32	13	27	43.41	46	40	39
WDT	5261	855	8054.3	950	2352	946	1667	720
% EPH	100	59	99	97	93	78	99	97
% NPV	0	-16	-12	-138	11	6	-21	-18
% WDT	-414	16	-1395	-76	-149	0	-91	18
	REF 2							
	COST OPTIMAL							
Wall	11	0	8	0	10	8	9	9
Roof	-	-	-	-	11	10	10	10
Floor	-	-	-	-	11	7	10	10
Wind	0	DL	0	0	DH	TL	0	0
Boiler	STD	STD	STD	STD	STD	MD	STD	STD
Vent	STD	MVS	STD	STD	STD	STD	STD	STD
EPH	25	38	4	25	48	60	27	27
NPV	12	32	6	7	31	36	18	18
WDT	3333	875	2348.8	687	1951	998	684	684
% EPH	65	46	83	0	79	74	74	74
% NPV	39	-61	18	0	51	43	37	37
% WDT	-153	34	-242	0	-144	-25	18	18
	ENERGY OPTIMAL							
Wall	12	0	6	3	11	8	12	10
Roof	-	-	-	-	12	11	11	11
Floor	-	-	-	-	11	8	12	10
Wind	TH	TL	TL	TL	TH	TL	TH	DH
Boiler	CD	MD	STD	CD	CD	MD	CD	MD
Vent	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EPH	0.735	35	0.3	0.7	26.5	44	2.9	5
NPV	29.72	33	26	28	43.16	45	37	35
WDT	4641	839	1508.7	968	1654	875	1102	975
% EPH	99	50	99	97	88	81	97	95
% NPV	-50	-66	-243	-300	32	29	-25	-18
% WDT	-253	36	-120	-41	-107	-10	-32	-17

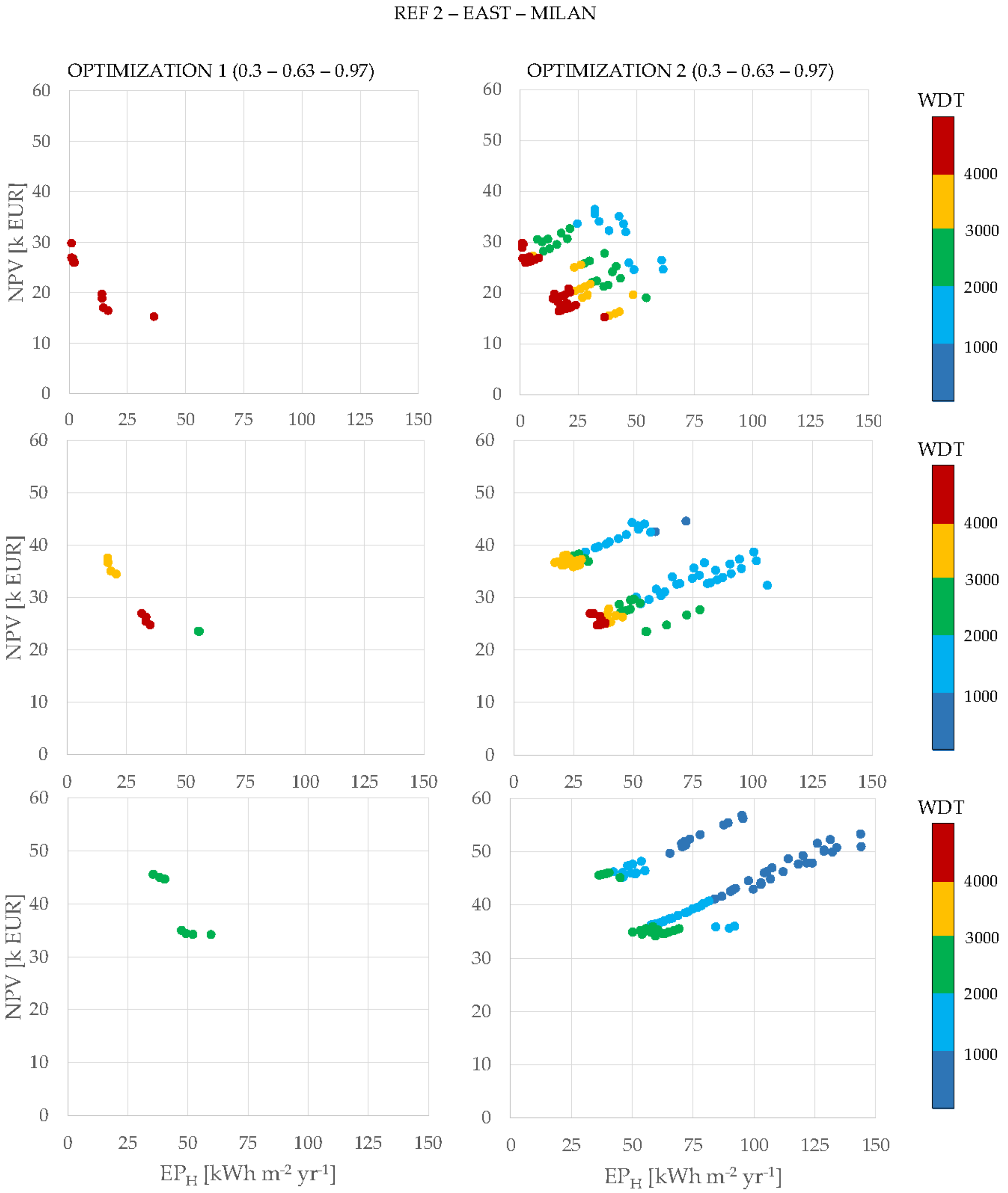

Fig. 1 – Pareto fronts of the Optimization 1 and 2 for the cases REF 2, windows east oriented, located in Milan according to the compactness ratios. The Weighted Discomfort Time represents the comfort performance, grouped according to the comfort level

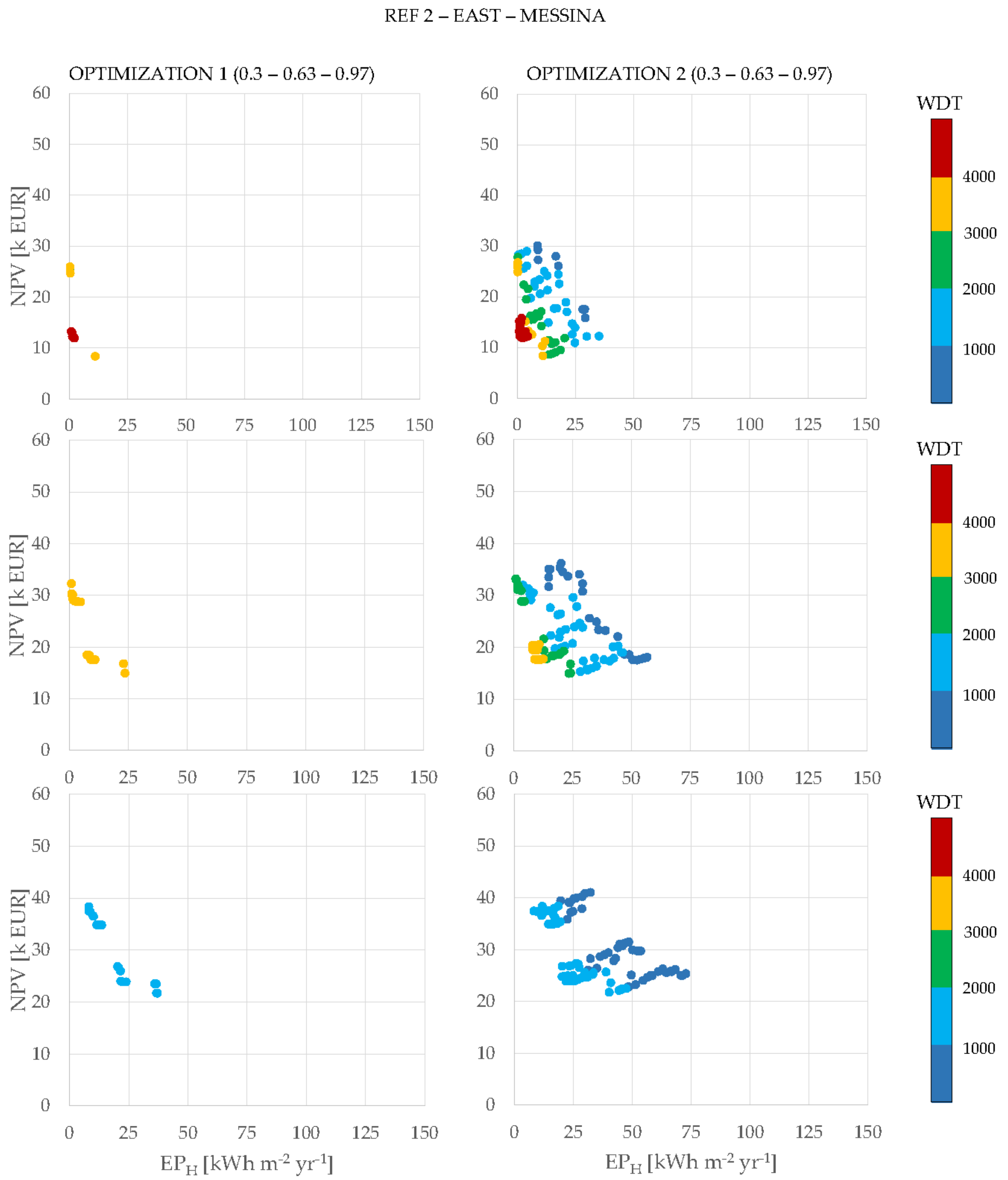

Fig. 2 – Pareto fronts of the Optimization 1 and 2 for the cases REF 2, windows east oriented, located in Messina according to the compactness ratios. The Weighted Discomfort Time represents the comfort performance, grouped according to the comfort level.

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