Multi-objectives optimization of Energy Efficiency Measures in existing buildings

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Abstract

The enhancement of the energy performance of the existing buildings stock is nowadays a priority. To promote buildings energy renovation, the European Committee (2010) [1] asks Member States to define retrofit strategies finding cost effective solutions. This so-called cost optimal approach, described by the Commission Delegated Regulation EU (European Commission, 2012) [2], pursues a balance of energy and economic targets, but currently neglects some important aspects, such as indoor thermal comfort. This research investigates the relationship between the initial characteristics of residential buildings and the definition of optimal retrofit solutions in terms of either maximum economic performance, or energy consumption minimization towards nZEBs behaviour for the lowest achievable thermal discomfort. A multi-objective optimization has been carried out using a genetic algorithm (NSGAII) coupled with adynamic simulation tool. The results demonstrate that (i) with conventional Energy Efficiency Measures, it is possible to approach the zero-energy target maintaining the economical convenience but worsening the indoor thermal comfort and that (ii) there is the necessity to introduce incentives to foster solutions not economically profitable, but more efficient in terms of energy savings and indoor thermal comfort.

Key words: Multi-objective Optimization, Building Retrofit, nZEBs, Energy Efficiency Measures, Dynamic Simulation

1. Introduction

The refurbishment of existing buildings is one of the main concerns of the national energy policies worldwide, especially in Europe. In fact, it is estimated that the average 2050 city will be already built for more than 70% considering the current rates of construction, demolition and renovation across Europe [3]. Since the publication of the Energy Performance of Buildings Directive (EPBD) recast [1] and the Energy Efficiency Directive [4], the European Commission is encouraging Member States (MSs) to identify policies able to stimulate deep renovations in a cost-effective way. Deep renovation means application of Energy Efficiency Measures (EEMs) able to transform existing buildings into Nearly Zero Energy Buildings (nZEBs) not only with standard technologies, such as insulating materials, insulated windows, advanced heating and cooling systems and modern lighting, but also using innovative technologies based on renewable energy sources. However, the regulation [2] suggests firstly to reduce the energy needs introducing gradually the most standard technologies and in a second time adopting more innovative solutions.

Moreover, the EPBD recast asks MSs to define new energy performance requirements for new and existing buildings by means of a cost optimal analysis. According to this approach, the energy performance requirements should stimulate the designer to define a mix of EEMs able to minimize the total cost along the lifespan of the building. By minimizing the Net Present Value (NPV), a utility function that accounts for both investment and operational costs, itis possible to find a balance between economic and energy targets, which represents a feasible performance requisite. By minimizing the energy consumption, the optimal EEMs combination could be used as a reference for the nZEBs performance, even if not specified in the directive. Even though the economic and energy aspects are of major importance to promote buildings refurbishment, some attention should be paid to verify the impact of the retrofit actions on the indoor environmental conditions. In fact, the EEMs should possibly reduce the building energy consumption while improving, or at least not deteriorating, the indoor thermal conditions for the occupants. In this respect, the attainment of objectives characterized by a competitive nature complicates the identification of retrofit solutions. Once stated the objective functions, a wide selection of EEMs has to be evaluated in order to find the optimal combination. This is not an easy task because of the large domain of the optimization problem. To limit the calculation effort, some authors tackled the problem a variable at a time: the insulation thickness of the opaque envelope [5–7] or the configuration of the glazing systems [8]. Some others limited the number of cases, considering only a set of predefined EEMs combination alternatives [9]. These approaches, which are useful to assess the sensitivity of the performance to some specific families of EEMs, lead to suboptimal results in general terms. On the other hand, the extensive evaluation of all the possible combinations of EEMs through a full factorial plan, can be extremely time consuming and difficult to handle [10]. The application of optimization techniques can overcome this problem, allowing the analysis of the entire dimension of the problem while reducing considerably the computational time. Ihm and Krarti [11] compared the results obtained calculating the full factorial plan with the sequential search optimization technique and demonstrated that the algorithm finds the same solutions with a computational time significantly lower. Different optimization techniques are used to investigate some particular aspects such as the building shape [12], the building envelope components [13–15], the configuration of curtain walls [16], or to define the optimal operation and management of the HVAC system [17–19]. Other authors analyze both the building configuration and the HVAC system [20–22]. Most of the times, the attempts to apply those techniques in multi-objective optimization have focused on two objectives, the energy consumption and the cost. The latter has been defined either as the Net Present Value (NPV) [10,15,17,20,23–28], or the investment costs [29] or the life cycle cost [11,30]. Some authors focused on the achievement of the environmental impact minimization in addition to the energy demand and cost minimization [15,22]. In the literature there are also some studies considering the optimization of the energy and comfort performance [16,31–34]. However, very few works considered the thermal comfort as a third objective in addition to energy performance and cost minimization [15,20]. This work aims to optimize the retrofit actions on residential buildings with a holistic approach. The analyzed EEMs are conventional technologies, applied on both the envelope components, and the heating and ventilating systems. More innovative solutions based on renewable energy sources are not considered in this work, because standard retrofits generally require lower investment costs and are more affordable for the users. Moreover, to enhance the relative contribution of renewable sources, the introduction of the innovative solution should generally follow the reduction of the energy needs of a building. Therefore, it was important to understand to which extent standard retrofit measures could approximate a nearly zero energy behaviour. The analysis is conducted on a quite large set of reference residential building modules, located in two different climatic contexts, to generalize the results representativeness to the existing buildings' stock. Firstly, the relationship between the initial building characteristics and the definition of optimal solutions, then the possibility for each reference building to be transformed into nZEBs, while minimizing the discomfort for the occupants, have been assessed. The approach proposed by the Regulation 244/2012 has been used to calculate for each solution the related Net Present Value (NPV). The Energy Performance (EPH) for heating and the evaluation of the indoor thermal comfort in terms of Weighted Discomfort Time(WDT) have been calculated by means of TRNSYS 17. The optimization of economic and energy performance, and indoor thermal comfort has been carried out through the NSGAII algorithm implemented in MATLAB. Finally, the congruity of the current government incentives has been evaluated considering the entity of government subsidies required to promote the transformation of the existing buildings towards nZEBs target, supporting solutions optimal in terms of energy savings and indoor comfort conditions, but not economically profitable, which is prescribed by the EPBD recast.

2. Definition of the reference buildings

The multi-objective optimization analysis focuses on different residential buildings obtained as variations of a reference single storey module with a square floor of 100 m^2. This floor area is sized on the weighted average surface for European residential buildings computed from the data provided by the UNECE technical report [35]. The vertical walls are oriented towards the main cardinal points and the window to floor ratio is equal to 14.4 %.

A set of 12 buildings has been developed by modifying some characteristics of the reference module in order to describe different reference residential configurations with the same geometrical features, but with different architectural typologies, according to the compactness ratio (S/V) and construction period. The sample size and the screening analysis, that individuate the variable affecting the results [36], allow to extend the representativeness of the research by investigating the influence of the reference buildings' characteristics on the definition of the optimal solutions. In particular, the choice of different compactness ratios (Fig. 1) allows to generalize the results by considering a detached house like typology (S/V =0.97), a penthouse like (S/V = 0.63) and an intermediate flat in multi-story building (S/V=0.3). Similarly, two starting envelope thermal characteristics have been modelled to account for the standards related to different construction periods. An opaque envelope resistance of 0.97 m^2 K W^1 and 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) represented the typical envelopes for constructions built prior to the first Italian energy legislation, in 1976 [37], and not yet renovated (REF 1). Differently, an opaque envelope resistance of 2.04 m^2 K W^1 (REF 2), with the same glazings of REF 1, is used for constructions built between the first and the second energy legislation (1976 ÷ 1991) [38]. The two-dimensional thermal coupling coefficients for thermal bridges in the reference cases, calculated according to the EN ISO 10211 [39], 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 0.06 W m^1 K^1 for the windows perimeter. The infiltration rate is calculated according to the UNI EN 12207 [40] and the EN 15242 [41] for all the building reference configurations. The reference air tightness n_{50} is 7 ACH and the associated infiltration rates are reported in Table 1 for the different S/V ratios.

The reference heating system is a standard boiler coupled with radiators and on off control system. The weather conditions of Milan (HDD_{20} = 2404 K d), as representative of a climate of Northern Italy (Climatic zone E in the Italian classification; Cfa according to Köppen [42] classification) and of Messina (HDD_{20} = 707 K d), representative of Southern Italy (Climatic zone B in the Italian classification; Csa according to Köppen classification), have been considered.

3. Energy Efficiency Measures (EEMs)

The research aims to analyse specifically the possibilities to transform a building into nZEBs, without considering renewable energy source based solutions and using standard measures that just effect the reduction of the primary energy of the building. The following EEMs have been considered:

i) external insulation of the walls with a thickness from 1 cm to 20 cm incremented by 1cm;

ii) external insulation of the roof with a thickness from 1 cm to 20 cm incremented by 1cm;

iii) external insulation of the floor with a thickness from 1 cm to 20 cm incremented by 1cm;

iv) replacement of existing glazing systems with higher thermal performance windows such as double or triple plane with either high or low solar heat gain coefficients. Besides, also the frames are replaced with an improved aluminium frames with thermal break;

v) substitution of heating generator with modulating or condensing boiler with a climatic control system;

vi) installation of a mechanical ventilation system with heat recovery to control the air exchange.

Additionally, the above listed EEMs cause some extra energy performance improvements without any additional costs:

- the linear thermal transmittances of thermal bridges are reduced according to the different insulation thickness and to the glazing type. The linear thermal transmittances were computed by means of a finite element analysis [43], considering a progressive increase of 5 cm of insulation on the building elements. Starting from these results, a polynomial regression was estimated and adopted in the Multi Objective Optimization code to calculate the variation of the thermal bridges effect;

- the air tightness of the building is assumed to be improved in the case of substitution of the windows and the value of the infiltration rates is considered as a half of the original values, reported in Table 1.

Although the replacement of the boiler is considered, the substitution of the radiators as emission system is not planned. In particular, the kind and nominal capacity of radiators does not change. This means that if a climatic control is used, the radiators supply temperatures can be lower than the designed one.

The prices of the different EEMs (Table 2) are defined from the comparison of different regional databases (Regional Price List, RPL, of Lombardia, Lazio and Sicilia). The RPL of Lazio is chosen because it represents a good reference for North and South Italy prices.

4. Multi-objectives optimization

4.1 Genetic Algorithm (GA)

The possibility to define retrofit strategies able to optimize multiple conflicting objectives, such as the maximization of the energy efficiency, the minimization of global costs of the building over a 30years lifespan and of the indoor thermal discomfort, is based on the concept of dominance of a general solution X over a solution Y within the so-called Pareto optimization. This approach does not generally lead to a single optimum but to a set of dominating solutions. According to Pareto, a solution X is said to dominate the other solution Y if both the following conditions are true:

i) The solution X is no worse than Y in all objectives;

ii) The solution X is strictly better than Y in at least one objective.

Thus passing from Y to X produces an improvement for all the objectives, or an improvement for some, without the other ones be harmed. The Pareto’s optimum or optima are solutions for which no alternatives exist that increase the fulfilment of an objective without hampering the attainment of another, or, in different words, nondominated solutions. When the problem treats two objectives, the result is the so called “Pareto front”, but when there are three objectives, as in the proposed case, the result is a “Pareto surface”.

The algorithm used to perform the optimization of the EEMs is the elitist Nondominated Sorting Genetic Algorithm (NSGAII) developed by Deb et al. [44]. The GA is an optimization technique used the first time in 1975 by Holland [45], which has gained an increasing relevance due to its ability to work with a population of individuals that converges to nondominated solutions. According to this method, inspired by the evolutionary theory, the individuals of a population represent all the possible solutions of the problem, in this case, a possible combination of EEMs. The genetic characters of each individual are located in a chromosome defined as a gene sequence. This contains the values of the input variables, i.e. the six kinds of retrofit interventions from *i* to *vi*.

As represented in Figure 2, the first step in the GA procedure is the selection of the initial population. Through Sobol's sequence sampling, 128 individuals are defined from all the possible combinations of EEMs. This pseudo random number generator avoids the oversampling of same region that can occur with random sampling [46]. Moreover, Sobol's sequence is a low discrepancy sequence, which aim to give a uniform distribution of values and it has the advantages of reducing the random behaviour of the genetic algorithm and giving a good individuals' collection as initial population. The fitness function to minimize is defined, according to Equation 1, as:

$$\begin{cases} EP_H = f_1\,(x_1, x_2, x_3, x_4, x_5, x_6); \\ NPV = f_2\,(x_1, x_2, x_3, x_4, x_5, x_6); \\ WDT = f_3\,(x_1, x_2, x_3, x_4, x_5, x_6); \end{cases} \qquad (1)$$

where x_1, x_2, x_3 represents the level of insulation of external walls, roof and floor, x_4 the adopted glazing system, x_5 the boiler type and x_5 the presence of the mechanical ventilation system. The fitness function, used in the analysis, is a Matlab code [47] that launches automatically the TRNSYS [48] model for the building energy simulation. After the model execution, the function reads the TRNSYS output file and postprocesses the results of simulation in order to compute the other two objectives. The three objectives function of the analysis are described in the sections 4.2 to 4.4 Once the fitness function is evaluated, the GA proceeds with the selection of the best individuals that are used as parents of the following generation. In this study, a fraction of 0.5 of tournament selection without replacement (TSWOR) [49, 50] has been adopted. Afterwards, the code combines the genetic characteristics of both parents, giving rise to the new generation. The implemented recombination procedures is based on the operators of crossover and mutation, which allow to investigate the entire size of the problem, preserving the diversity of the solutions. Crossover mates and swaps part of the genes of the parents' chromosomes; in this case, the adopted arithmetic crossover fraction is 0.8. The mutation is a random alteration of a gene. By means of Mersenne-Twister pseudo random generator [51], a randomly selected gene is replaced by a uniformly distributed random value that meet the gene range. The iterative process is repeated until the maximum number of iteration or the convergence level is reached. The convergence criteria are met when the genetic variability between the parental and the filial generation are lower than a fixed level. The final population then contains the optimal solutions.

4.2 Weighted Discomfort Time (WDT)

The evaluation of the long-term comfort performance is conducted by means of the calculation of the Discomfort Weighted Time (WDT) index, as proposed by annex F of the Standard EN 15251 [52] through the Degree Hours Criteria. With this approach the occupied hours, during which the actual operative temperature lies outside the specified comfort range, are weighted by a weighting factor which depends on the entity of the deviation from the range (Equation 2 and 3). The comfort range of operative temperature is defined on the base of a normal level of expectation (Category II) for an activity level of 1.2 met and a clothing index of 1 clo. During the heating season, defined according to the D.P.R. n.74/2013 [53] based on the Italian Classification of Climatic zones, the lower and upper values for the operative temperature (20 °C to 25 °C) are fixed.

$$\mathrm{WDT}=\sum \mathrm{wf} \cdot \mathrm{time} \tag{2}$$

$$\mathrm{wf} = \Theta_o - \Theta_{o,limit}$$

$$\text{when } \Theta_o < \Theta_{o,limit,lower} \text{ or } \Theta_o > \Theta_{o,limit,upper} \tag{3}$$

During the rest of the year (when no heating system works), the comfort range is calculated considering the adaptive comfort approach. The acceptable operative temperature range is defined according to annex A of the Standard [52], as follow (Equation 4a and 4b):

$$\Theta_{o,limit,upper} = 0.33\ \Theta_{rm} + 18.8 + 3 \tag{4a}$$

$$\Theta_{o,limit,lower} = 0.33\ \Theta_{rm} + 18.8 - 3 \tag{4b}$$

Those limits are based on the thermal experience of an individual defined with the exponentially weighted running mean of the daily outdoor mean air temperature, Θ_{ed}, calculated as a series of the seven days immediately before the analysed one:

$$\Theta_{rm} =(1-\alpha)\cdot(\Theta_{ed1} + \alpha\ \Theta_{ed2} + \alpha^2\ \Theta_{ed3} + \ldots + \alpha^6\ \Theta_{ed7}) \tag{5}$$

The evaluation of the WDT was tightly integrated into the simulation model in TRNSYS.

4.3 Energy Performance for heating (EP$_H$)

The Energy Performance for heating (EP$_H$) is calculated by means of the simulation tool TRNSYS. The national Test Reference Years of Milan and Messina [54] are used to simulate the weather conditions. The multizone building subroutine, Type 56, is used to define the thermophysical properties of the building. The heating system is modelled through the Type 869 [55, 56]. This subroutine is able to simulate the behaviour of different heating systems, such as modulating and condensing boiler. A thermostat switches on the boiler when the indoor air temperature is lower than 20 °C, and switches it off, when it overcomes 22 °C. In combination with replacement of the standard boiler with a more efficient one, the equipment of an outside sensor, that regulates the water supply temperature in relation to the outside temperature, is considered. The internal gains, a half radiative and a half convective, are modelled in agreement with the Italian technical specification UNI/TS 11300 [57]. The technical specification also defines the occupancy schedule and the gains' values according to the room type and activity, as reported in Table 3. Half of the building's area is considered living area and the other half bedrooms.

The air change rate, during the occupancy time, is set to 0.5 ACH. When the mechanical ventilation system is considered, the same air change rate is set during the occupancy time, but the indoor exhaust air is used to preheat the outdoor inlet air by heat recovery. In the summer season, the mechanical ventilation system is also operated to avoid the overheating of the indoor temperature. In this case, in fact, during the occupied and not occupied period, whenever the operative temperature overcomes the upper limit of the comfort range (the occupants feel warm) 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. During the occupied periods, if the outdoor conditions are worse than inside (too cold or too hot), the mechanical ventilation is operated with a fixed airflow rate of 0.5 ACH with heat recovery.

4.4 Net Present Value (NPV)

The economic evaluation of the different EEMs is conducted according to the comparative framework methodology of cost optimal level, proposed by the EU 244/2012 [2]. The Net Present Value (NPV) of the possible combinations of retrofit solutions is calculated to define their associated economic benefits. This approach allows the analysis of different time series of cash flows related to each interventions. The NPV is evaluated for a lifespan of 30 years and it takes account of:

- the initial Investment Cost (IC) for the retrofits;
- the annual running costs, composed of the Annual Energy Cost (EC) for the Energy Performance for Heating (EP_H) and the Maintenance Cost (MC), for preserving and restoring the building and its elements;
- the replacement cost (RC), for the periodic substitution of building/system elements;
- the residual value (RV) for the pieces of equipment with longer lifespan according to EN 15459 [58].

To determine the Energy Cost, the fuel and electricity price rising is also considered (Table 4).

4.5 Definition of government incentives

In Italy, the investments for energy retrofitting of those residential buildings which fulfil a specified energy requirements, are currently funded with a tax relief in ten years of 65 % of the investment cost, which is going to decrease to 50 % from next year. The pay back in 10 years leads to a discounted percentage that is actually much lower than its nominal value. Moreover incentives are given just up to a total amount of 60 000 EUR for each residential unit or 100 000 EUR for common parts of multi-flat buildings.

The government incentives should be able to promote the employment of most efficient building energy retrofits, in particuar they should support the transformation of the existing buildings into nZEBs going beyond the cost optimal solutions. To define the actual amount of incentive able to make most efficiency solutions, in terms of energy savings and indoor thermal comfort, also economically viable in a rational way, the NPV of the cost optimal solution of each cases can be taken as a reference (hereafter called NPV_{opt}). Subsequently, the solutions with better EP_H than the cost optimal are selected. According to the multi-objective optimization approach, among those solutions, the ones with lower WDT than the reference case and the cost optimal solution are considered. The solution with the best EP_H is then chosen as the conventional EEMs-based nZEBs target and the amount of incentive needed to make it as profitable as the cost optimal ones is calculated as the difference between its NPV and NPV_{opt}:

$$\Delta NPV = (NPV_{ref} - NPV_{opt}) \tag{5}$$

To compare this net incentive with the law levels, the equivalent annual rates (AR) are calculated for a period of 10 years with a discount rate (dr) of 3%, dividing the total incentive by the discount factor for identical annual payments (DF) as follows:

$$AR = \Delta NPV/DF \tag{6}$$

$$DF = ((1+dr)^{10} -1)/(dr \cdot (dr+1)^{10}) \tag{7}$$

Finally, the percentage of incentive cost (TI) is quantified as the cumulated flow divided by the Investment Cost (IC):

$$TI = 10 \cdot AR / IC\% \tag{8}$$

5. Results

In Figures 3 and 4 the results of the optimization process have been reported for the cases with windows south exposed, according to different climates, S/V ratios and thermal properties of the opaque envelope (cases REF 1 and REF 2). The dots on the graphs correspond to the nondominated solutions, in other words to the solutions for which no alternatives can be found that increase the fulfilment of an objective without the other ones being harmed. The graphs show the relationship between the Net Present Value (NPV) and the Energy Performance for heating (EP_H), while the different colours represent the Weighted Discomfort Time (WDT), ranging from blue, for the solutions with the lowest value of WDT, to red for the highest WDT. The performance of the starting building configurations (reported in Table 5) are not included in the graphs.

The relationship between EP_H and WDT and the typology of EEMs has been shown in Figure 5. In those graphs, the clustering of the optimal solution of the Pareto surfaces according to typology of glazing and to the presence of mechanical ventilation is highlighted.

Table 6 and 7 report the configuration of the Costs, Energy and Comfort optima according to the analysed reference cases. From the results, it is possible to identify the best combinations of EEMS, and to understand the relationship between the considered retrofit strategies and the attainment of the different objectives.

Finally, Table 8 shows the investment costs and the total incentives calculated as IC percentage. The investment cost is related to the solution with the best EP_H and with WDT lower than the reference case and the cost optimal solutions. The incentives are calculated as a percentage of the total investment necessary to make the most energy performing solution among the multi-objective optima as profitable as the cost optimal ones.

6. Discussions

6.1 Pareto Surfaces

Observing the Figures 3 and 4, the climatic conditions and the different compactness ratios seem to be the most influential quantities for the definition of the optimal solutions and the configuration of the Pareto surfaces. The thermal characteristics of the opaque envelope affects more the cost effectiveness of the EEMs than the other performances.

Generalizing, the economic efficiency of the retrofit strategies is greater for the cases with higher heating needs, because of the greater opportunity to reduce the energy costs. In fact, for the cases located in cold climates (Milan), with larger dispersing surfaces and lower thermal performance of the opaque envelope, the running costs represent the bigger cost item in the definition of NPV. The EEMs for those cases can deeply reduce the heat losses and improve the energy performance of the building. On the other hand, the better the starting conditions, the more difficult is to define economically advantageous solutions. In the hottest climate (Messina) and for the smallest compactness ratio (S/V=0.3) the economic efficiency of the energy refurbishment it is not always feasible.

As for the energy performance, the cases with lower heating needs (hottest climates, smaller compactness ratio, better thermal characteristics, windows south oriented) clearly lead to better energy performance.

In terms of comfort, the cases with the worse indoor thermal conditions are the ones characterised by smaller compactness ratio, located in Milan and with windows east oriented. The smaller the external surface, the bigger is the summer overheating, because it gets more difficult to get rid of the excess of heat through the external environment. The higher level of WDT, which occurs in the cases located in Milan or with the windows East exposed, is due to the lower altitude of the solar angle. In the morning, but also for higher latitude, the lower position of the sun allows the entrance into the building of a bigger fraction of beam solar radiation.

Considering the results in more detail, it is possible to identify two clusters of points on the graphs. This clustering is more evident for Milan and for the cases with bigger compactness ratio. The points with higher NPV values represent the solution with the mechanical ventilation system. The high investment cost related to this technology influences considerably its economic effectiveness. Analysing the relationship between EP_H and WDT and the typology of EEMs, the optimal solutions of the Pareto's surfaces are grouped by typology of glazing and according to the presence of mechanical ventilation system. Figure 5 highlights that the typology of the glazing system is the strategy with the highest influence on the attainment of comfort conditions. In particular, the solutions with better comfort performance are the ones with low SHGC. Moreover introducing the mechanical ventilation system leads to lower energy consumption and to higher indoor thermal comfort conditions.

6.2 Energy, Cost and Comfort optima

The analysis of the results in terms of energy, cost and comfort optima, have led to highlight the packages of EEMs that have to be used to optimize the different objectives, as discussed following.

The cost optima are mainly characterised by the introduction of high level of insulation thickness and by the substitution of the glazing system with double and high SHGC glazing system. The large thickness of insulation and the substitution of the single pane glazing lead to a significant reduction of the heat losses during the cold season and, because of the reduction of the energy consumption, increasing the economic efficiency of the retrofits. It is possible to observe that the insulation thickness used in cost optimal solutions decreases with the decrease of reference cases heating needs, which is due to the difficulty to recover the investment costs in the cases with a better starting performance. If the cost optima present high reduction of the energy consumption, on the other hand, they are characterised by a significant worsening of the indoor thermal conditions.

Under an economic point of view, the efficacy of the EEMs is greater for the cases with higher heating needs, in Milan the NPV of the reference cases compared with the ones of the cost optimal solutions is reduced in a range from 31 % to 54 %, while in Messina from 18 % to 37 %. This is due to the greater opportunity for the cases with predominant heating needs to reduce the maintenance cost for the energy supply that represents the bigger cost item in the NPV. The cost optimal solutions present very high reductions of the energy consumption (from a minimum of 57 % to 92 % for the cases located in Milan and from 66 % to 96 % for Messina), but the indoor thermal comfort is always worsened. In the worse cases both in Milan and in Messina the WDT is even five times bigger than the reference cases

The best solutions in term of energy are similar to the cost optima, but they present higher insulation thickness, triple glazing with high SHGC, a more efficient boiler and the mechanical ventilation system. The buildings located in Messina and the ones with smaller compactness ratio can achieve energy performance close to zero. For those buildings, it exists the possibility to reach nZEBs target with standard retrofits. On the contrary, for the cases with greater compactness ratio located in Milan, even with the addition of heavy thicknesses of insulation, the substitution of the glazing and the boiler and the addition of the mechanical ventilation system, it is not possible to achieve energy consumption very close to the zero. Probably for those cases, it would be necessary to consider the introduction of renewable energy source-based solutions in addition to standard EEMs, to transform the building into ZEBs. In all the cases considered, the energy optima are characterized by high value of WDT, because the high level of insulation and the introduction of glazing with high SHGC, causes overheating conditions.

The energy performance of the reference case can be highly increased, in Milan in the range of 8599 %, while in Messina in the range of 90100 %. The lower increments of energy performance occur in buildings with predominant heating needs (large compactness ratios). Generally, the energy optima in Milan present a decrease of the NPV compared to the reference case (until the 50 % less), but in the cases with better thermal performance and smaller compactness ratio the economic profitability is compromised and the NPV results 50 % bigger than the reference case. In Messina the energy optima are never economically profitable, the NPV is worsened in the range of 12 until 243 %. Some internal comfort issues rise due to the recourse of high levels of insulation, and the WDT is always bigger than the one of the case without retrofits;

For the comfort optimal solution, the level of insulation of the opaque envelope is not very important in some cases it is not even considered but the substitution of the single pane glazing with the low SHGC ones and the introduction of the mechanical ventilation system seem to be crucial. In contrast, the thermal insulation of the opaque envelope seems to be the retrofit responsible of summer overheating: in super insulated buildings a small energy input raises the internal temperature significantly and if the extra heat it is not dissipated, the liveability of the indoor environment is threatened. The use of low SHGC leads to better comfort performance, because it reduces the risk of summer overheating. The competing nature of the objective functions is clearly visible in the comfort optimal solutions: improving the indoor thermal comfort in most of the cases is not economically effective and the reduction of the energy consumption is lower compared to the others optima.

This is likely to induce behavioural interactions of people with the building in order to prevent discomfort conditions, which could heavily compromise the designed performance. In Milan the reduction ranges from a minimum value of 38 % to a maximum of 66 % and in Messina from 24 % to 79 %. In most of the cases the comfort optima are not economically effective. In Milan the variation of the values of NPV depends on the building configuration, in some cases (smaller S/V) is worsened (until 65 %) in other it is reduced (until 30 %). In Messina the improvement of comfort performance is never convenient, the NPV is worsened in the range of 15 until 252 %. What it is evident is that improving the energy efficiency of the buildings leads a significant worsening of the WDT.

6.3 Government subsidies

The amount of the investment cost of the best energy solutions among the multi-objective optima (Table 8) increases with the increase of the compactness ratio. The values are higher in Milan than in Messina, due to the higher economical effort requested to improve the initial performance of the buildings in cold climatic conditions.

The calculated public incentives have been expressed as a percentage of the total investment needed to make the best energy solutions as economically convenient as the cost optimal ones, in order to go beyond the cost optimal solutions, moving the existing buildings towards nZEB performance. The value of the TI percentages are higher for the cases with smaller S/V ratio and located in Messina, because of the difficulties to define economically advantageous solutions for the cases with better starting conditions (REF2). In fact, the better the starting cases, the bigger difference between the NPV_{opt} and the NPV_{ref} thus leading to the necessity of founding a larger percentage of investment costs.

Comparing the calculated incentives percentages with the ones applied by the Italian legislation, it is possible to see that in Messina, in most of the cases, the required incentives are higher than the actual subsidies (65 %). If the future subsidization (50%) were considered, the required incentives would be higher than the public ones in all the cases located in in Messina (the best solution should be founded from a minimum of 51 % to a maximum of 106 %) and also in almost all the configurations with S/V lower than 0,97 in Milan, where the minimum incentive percentages range from 37 % to 81 %.

7. Conclusions

In this paper a set of reference buildings has been analyzed with the purpose of investigating the influence of the reference buildings' characteristics on the definition of optimal retrofit solutions considering economic, energy and comfort performance. A Genetic Algorithm coupled with a simulation tool is used to investigate the most promising strategies able to optimize the three different competing objectives according to the Pareto approach. The cost-optimal and the energy optimal configurations have been investigated as the reference for the law performance requisites and for the nZEB performance target. The addition of thermal comfort allowed the analysis of these targets in relation to the quality of the indoor environment. Conventional EEMs, not relying on renewable energy sources, have been considered in order to maximize the building energy performance before introducing advanced and more expensive technologies, to enhance their relative impact while limiting the investment costs. The multi-objective analysis has demonstrated that the cost-optimal solutions lead to consistent energy saving (more than 57%) but the thermal comfort gets always worse. The energy optima are pretty close to the Zero-Energy condition in Messina and quite close in Milan, but the economic profitability is reached for few cases with higher heating demand.

Otherwise, those solutions which are economically convenient drastically increase the discomfort time. In warmer climate such as Messina the energy optima can be reached applying more expensive EEMs thus increasing the NPV and the thermal discomfort. The solutions with the best thermal comfort are those that require the highest investment costs and consequently, the highest NPV. These results demonstrate that with conventional EEMs it is possible to approach the zero-energy target maintaining the economical convenience but worsening the indoor thermal comfort. To increase the comfort condition in energy optimal solutions, some specific EEMs are required such as the low-SHGC windows and the mechanical ventilation, with a consequent increase of investment costs. For this reason, public incentives are necessary to promote the renovation of existing buildings towards nZEB. The percentage incentive of the investment costs to support the adoption of the energy optima configurations has been quantified and compared with the current Italian situation. Considering a multi-objective approach, the entity of the incentives to transform existing buildings towards nZEBs should always be higher than that proposed by the Italian legislation. Moreover, to prevent a worsening of indoor conditions, the incentive should be probably allocated on those measures able to improve the internal comfort. This study has been focused on residential buildings refurbishment without considering possible interactions of the occupants in the management of the windows opening nor of the shading closing: this way it was possible to compare the building passive energy, cost and comfort performance. Further investigations will be carried out in order to evaluate the influence of occupants' behaviour on the cost, energy and comfort-optimal solutions.

Nomenclature

Symbols

ACH	Air Change rate (h^{1})
AR	Annual Rate (EUR)
c	specific heat capacity, ($\mathrm{J\ kg}^{1}\ \mathrm{K}^{1}$)
DF	Discount Factor (%)
dr	discount rate (%)
EC	Annual Energy Cost (EUR)
EP	Energy Performance Indicator ($\mathrm{kWh\ m}^{2}\ \mathrm{yr}^{1}$)
HDD_{20}	heating degree days calculated with a reference temperature of 20°C (K d)
IC	Investment Cost (EUR)
MC	Maintenance Cost (EUR)
NPV	Net Present Value (EUR)
S	dispersing surface (m^{2})
$SHGC$	Solar Heat Gain Coefficient ()
TI	percentage of incentive Cost (%)
U	Thermal transmittance ($\mathrm{W\ m}^{2}\ \mathrm{K}^{1}$)
V	Conditioned Volume (m^{3})
WDT	Weighted Discomfort Time (K h)
wf	weighting factor (K)
x	insulation thickness (m)

Greek symbols

λ	thermal conductivity, ($\mathrm{W\ m}^{1}\ \mathrm{K}^{1}$)
Θ	temperature (°C)

ρ	density (kg m^3)

Subscripts

ed	referred to daily outdoor mean air
H	referred to heating
o	operative
rm	running mean
ref	referred to reference building
opt	referred to cost-optimal
VW	referred to vertical walls
HW	referred to horizontal walls

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Table 1: Infiltration rate values (ACH) according to the different characteristics of the reference building

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

Table 2: EEMs and associated investment cost without VAT

Opaque Envelope: Insulation Layer				
Thermal characteristic of Polystyrene EPS				***Investment Cost (EUR m^{-2})***
Thermal conductivity	λ (W m^{-1} K^{-1})	0.04		Vertical wall IC_{VW} = 160 x* + 38.53
Specific heat capacity	c (J kg^{-1} K^{-1})	1470		Horizontal wall IC_{HW} = 188 x* + 8.19
Density	ρ (kg m^{-3})	40		* thickness (m)
Transparent Envelope				
Thermal characteristic of glazing system				***Investment Cost (EUR m^{-2})***
		U (W m^{-2} K^{-1})	**SHGC**	
DH – Double, high SHGC (4/9/4, krypton, low-e)		1.140	0.608	IC_{DH} = 404.33
DL – Double, low SHGC (6/16/6, krypton, low-e)		1.099	0.352	IC_{DL} = 439.06
TH – Triple, high SHGC (6/12/6/12/6 krypton, low-e)		0.613	0.575	IC_{TH} = 477.65
TL – Triple, low SHGC (6/14/4/14/6 argon, low-e)		0.602	0.343	IC_{TL} = 454.49
Aluminium Frame with thermal break		1.2	-	Included in glazing price
Heating System				
Efficiency of the boilers				***Investment Cost (EUR m^{-2})***
Standard (STD)		89%		IC_{STD}=1000 EUR
Modulating (MDL)		96%		IC_{MDL}=1500 EUR
Condensing (CND)		101%		IC_{MDL}=2000 EUR
Mechanical ventilation system (MVS)				
Technical characteristics				***Investment Cost (EUR)***
Ventilation rate (m^3 h^{-1})		150		IC_{MVS}=6000 EUR
Power (W)		59.7		

Table 3: Internal gains according to the occupancy schedule

	Schedule	**Kitchen [W m^{-2}]**	**Bedrooms [W m^{-2}]**	**Total Gains [W]**
Week days	7 - 17	8	1	450
	17 - 23	20	1	1050
	23 - 7	2	6	400
Weekend	7 - 17	8	2	500
	17 - 23	20	4	1200
	23 - 7	2	6	400

Table 4: Parameters for the definition of the Energy Costs

Parameters for the economic analysis	
Fuel Cost	0.85 EUR Sm^{-3}
Lower Heating Value	32.724 MJ Sm^{-3}
Annual rate of increase fuel price	2.8 %
Electricity Cost	0.25 EUR kWh$_{el}^{-1}$
Annual rate of increase electricity price	1.71 %
Real Interest Rate	3 %
VAT	10 %

Table 5: Energy Performance for heating, Net Present Value and Weighted Discomfort Time of the reference cases in Milan (MI) and in Messina (ME) according to compactness ratio, thermal characteristics (REF1 and REF2) of the opaque envelope and windows orientations.

	S/V = 0.3				S/V = 0.63				S/V = 0.97			
	EAST		SOUTH		EAST		SOUTH		EAST		SOUTH	
	MI	ME	MI	ME	MI	ME	MI	ME	MI	ME	MI	ME
REF 1												
EP_H [kWh m^{-2} y^{-1}]	114	53	99	39	190	89	177	78	269	131	253	119
NPV [k EUR]	32	15	28	11	52	25	49	22	74	36	70	33
WDT [K h]	1445	911	1023	539	1170	951	946	727	865	973	775	875
REF 2												
EP_H [kWh m^{-2} y^{-1}]	85	38	70	25	166	77	154	66	244	117	230	106
NPV [k EUR]	24	11	20	7	46	22	42	19	67	33	63	30
WDT [K h]	1863	1142	1316	687	1329	1004	1055	744	916	948	799	836

Table 6: List of retrofit measures applied to the optimal solutions for Milano (MI) and Messina (ME), case REF 1. EP_H is expressed in (kWh m^{-2} y^{-1});NPV in (kEUR); WDT in (K h).

REF 1												
	S/V = 0.3				S/V = 0.63				S/V = 0.97			
	EAST		SOUTH		EAST		SOUTH		EAST		SOUTH	
	MI	ME	MI	ME	MI	ME	MI	ME	MI	ME	MI	ME
COST-OPTIMAL												
Wall	17	8	12	11	16	11	16	12	15	11	15	12
Roof	-	-	-	-	14	10	15	10	14	9	14	11
Floor	-	-	-	-	-	-	-	-	15	10	15	10
Wind	DH	DH	DH	0	DH	DH	DH	0	DH	DH	DH	0
Boiler	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Vent	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
EP_H	14	2	8	13	34	10	22	23	55	24	43	35
NPV	16	12	14	9	25	18	22	15	35	24	32	21
WDT	8057	5483	6337	1270	4995	3473	4255	877	3185	1802	2466	542
ENERGY-OPTIMAL												
Wall	18	6	17	18	18	18	18	20	18	19	19	18
Roof	-	-	-	-	20	19	19	18	20	18	18	20
Floor	-	-	-	-	-	-	-	-	19	19	19	18
Wind	TL	TH	TH	DH	TH	TH	TH	TH	TH	TH	TH	TH
Boiler	STD	STD	STD	STD	CD	CD	CD	CD	CD	CD	CD	CD
Vent	MVS	MVS	MVS	STD	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP_H	0.5	0.3	0.493	0.3	8	0.3	3	0.335	22	2	12.84	0.6
NPV	27	26	27.45	13	37	35	36	35.3	46	41	43.41	40
WDT	3946	3510	5261	8054	4418	3675	3598	3166	3049	2317	2352	1667
COMFORT OPTIMAL												
Wall	0	0	0	1	0	1	0	1	0	1	1	1
Roof	-	-	-	-	1	10	4	16	12	16	15	19
Floor	-	-	-	-	-	-	-	-	0	7	2	11
Wind	DL	0	DL	0	DL	TL	DL	0	DL	DL	TL	TL
Boiler	STD	STD	STD	STD	STD	CD	STD	STD	MD	MD	CD	CD
Vent	MVS	MVS	MVS	MVS	STD	MVS	STD	MVS	STD	MVS	MVS	MVS
EP_H	49	40	41	20	119	18	92	28	141	31	81	20
NPV	35	25	32	23	41	35	34	29	51	42	55	41
WDT	1133	754	855	481	1061	639	878	423	561	479	444	280

Table 7: List of retrofit measures applied to the optimal solutions for Milan (MI) and Messina (ME), case REF 2. EP$_H$ is expressed in (kWh m^{-2} y^{-1}); NPV in (kEUR); WDT in (K h).

REF 2												
	S/V = 0.3				S/V = 0.63				S/V = 0.97			
	EAST		SOUTH		EAST		SOUTH		EAST		SOUTH	
	MI	ME	MI	ME	MI	ME	MI	ME	MI	ME	MI	ME
COST-OPTIMAL												
Wall	11	11	11	8	10	11	11	10	10	9	10	9
Roof	-	-	-	-	11	11	11	9	11	10	11	10
Floor	-	-	-	-	-	-	-	-	11	9	11	10
Wind	0	0	0	0	0	0	0	0	DH	0	DH	0
Boiler	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Vent	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
EP$_H$	36	11	25	4	56	24	43	14	60	40	48	27
NPV	15	8	12	6	24	15	20	12	34	22	31	18
WDT	4198	3338	3333	2349	2866	2123	2189	1361	2586	1153	1951	684
ENERGY-OPTIMAL												
Wall	12	6	12	6	12	12	12	12	11	12	11	12
Roof	-	-	-	-	12	12	12	12	11	11	12	11
Floor	-	-	-	-	-	-	-	-	11	12	11	12
Wind	TH	TH	TH	TL	TH	TH	TH	TH	TH	TH	TH	TH
Boiler	CD	STD	CD	STD	MD	CD	CD	MD	CD	MD	CD	CD
Vent	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP$_H$	1	0.3	0.7	0.3	17	1	9	0	36	8	27	3
NPV	30	26	30	26	37	33	35	32	46	37	43	37
WDT	5427	3561	4641	1509	3638	2908	2930	2307	2206	1604	1654	1102
COMFORT OPTIMAL												
Wall	0	0	0	0	0	0	0	0	1	2	1	2
Roof	-	-	-	-	3	10	10	9	10	11	9	11
Floor	-	-	-	-	-	-	-	-	0	6	0	6
Wind	TL	TL	TL	TL	TL	TL	TL	DL	TL	TL	TL	TL
Boiler	STD	MD	MD	MD	MD	MD	MD	MD	MD	MD	STD	MD
Vent	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP$_H$	44	17	35	10	72	28	53	24	113	32	114	27
NPV	34	28	33	26	45	34	41	32	60	41	59	39
WDT	1132	566	839	359	951	542	748	376	535	503	442	317

Table 8: Investment Costs and Total Incentive percentages for different localities, thermal characteristics, windows orientations and compactness ratios.

	REF 1				REF 2			
	EAST		SOUTH		EAST		SOUTH	
S/V ratio	IC [k EUR]	TI percentage	IC [k EUR]	TI percentage	IC [k EUR]	TI percentage	IC [k EUR]	TI percentage
	MILAN							
0.3	23.053	**55 %**	24.987	**74 %**	21.855	**63 %**	23.372	**81 %**
0.63	30.574	**46 %**	30.368	**52 %**	26.732	**63 %**	26.827	**69 %**
0.97	35.404	**37 %**	35.124	**39 %**	30.958	**43 %**	31.164	**46 %**
	MESSINA							
0.3	21.988	**75 %**	22.462	**96 %**	23.372	**98 %**	21.456	**106 %**
0.63	26.400	**58 %**	25.774	**78 %**	26.414	**75 %**	25.473	**88 %**
0.97	31.988	**51 %**	27.709	**72 %**	28.915	**66 %**	28.915	**70 %**

Figure 1 Building with different compactness ratio used as reference residential building modules.

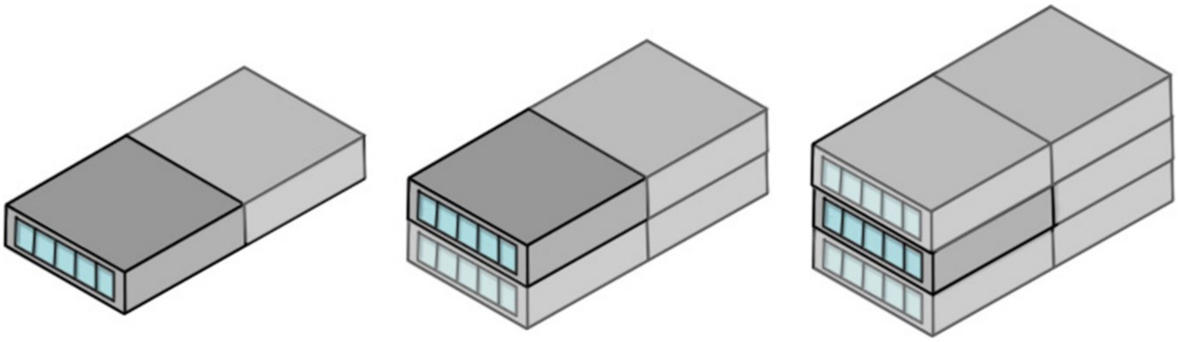


Figure 2 Flowchart diagram for the development of the optimization process.

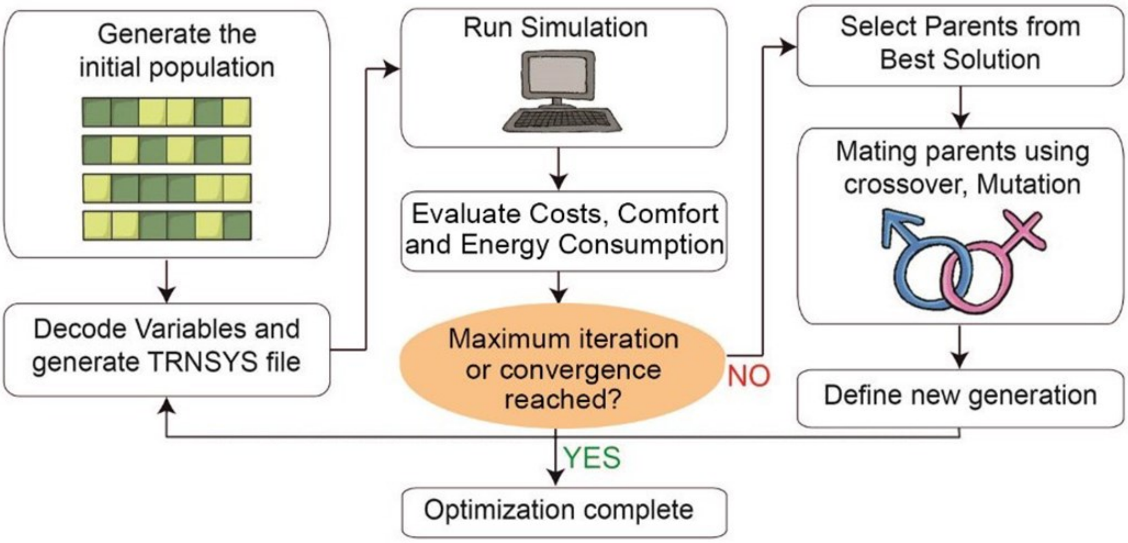


Figure 3 Pareto surfaces of different compactness ratio for Milan and Messina, cases REF 1 and south oriented windows. The Pareto surfaces are plotted on EP_H and NPV diagram. The weighted discomfort time is represented with the colored scale on the right.

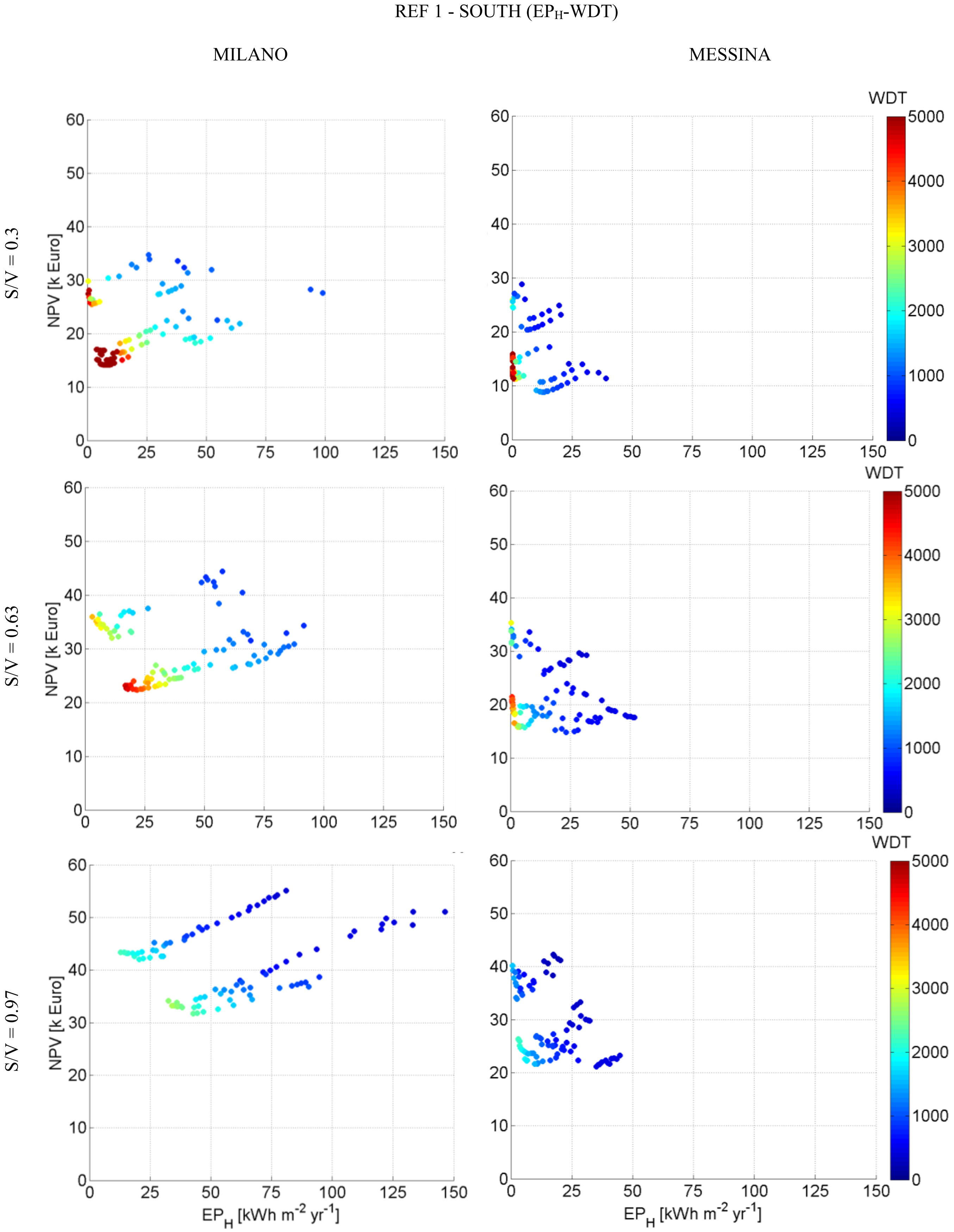
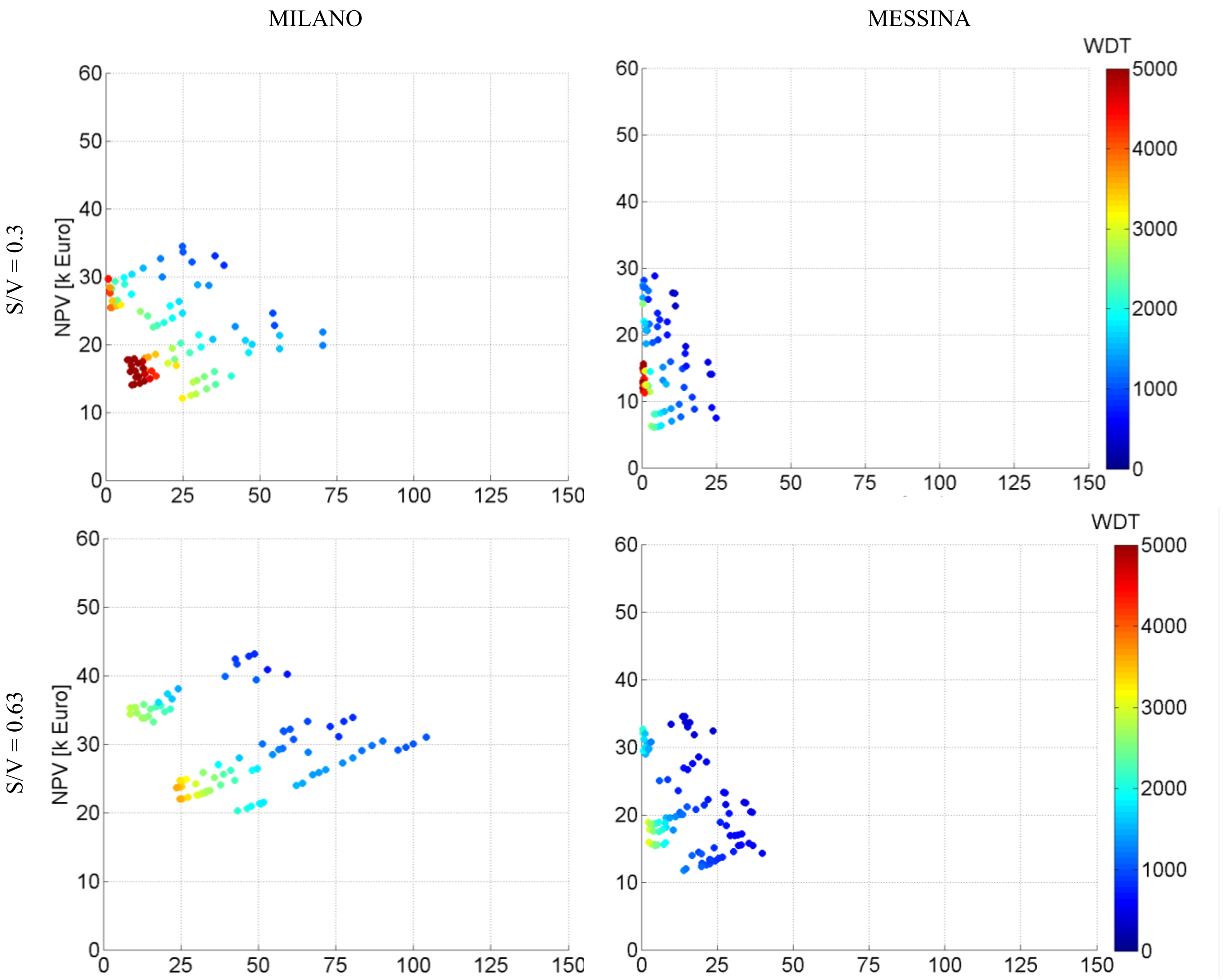


Figure 4 Pareto surfaces of different compactness ratio for Milan and Messina, cases REF 2 and south oriented windows. The Pareto surfaces are plotted on EP_H and NPV diagram. The weighted discomfort time is represented with the colored scale on the right.

REF 2 - SOUTH (EP_H-WDT)



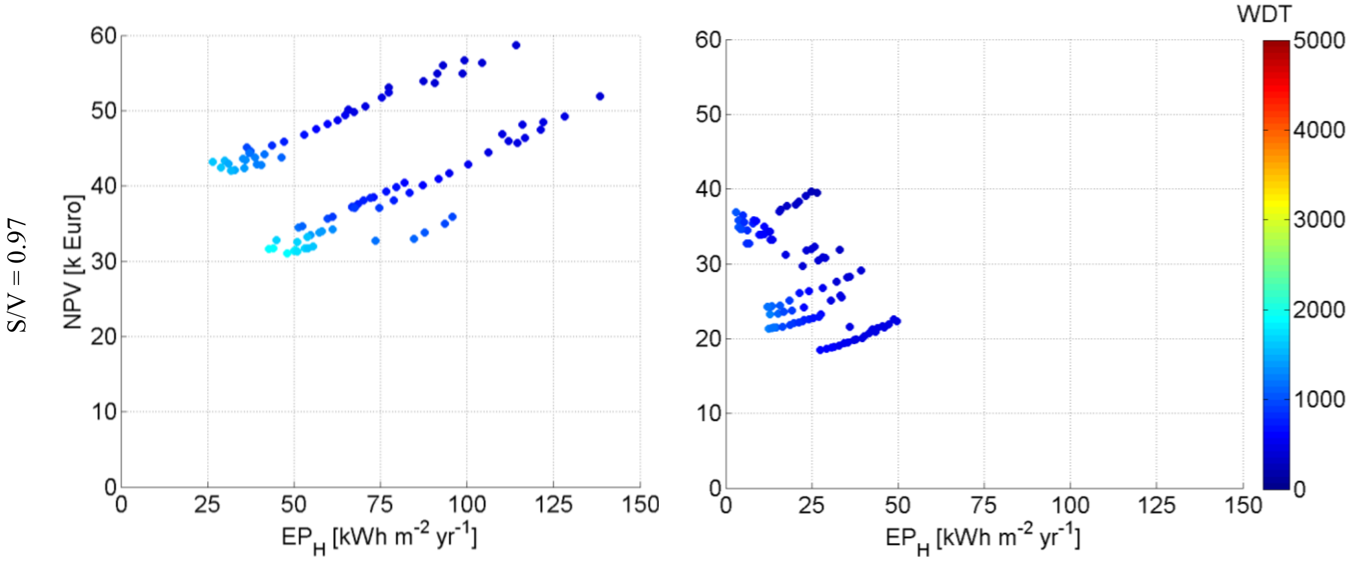
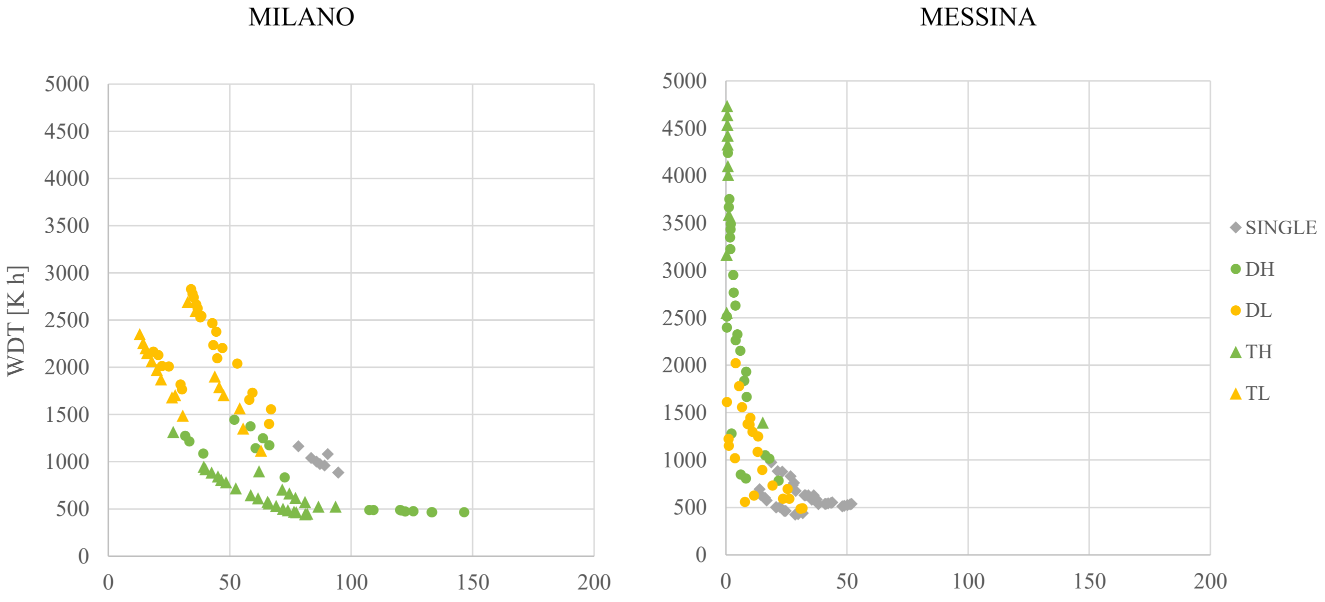
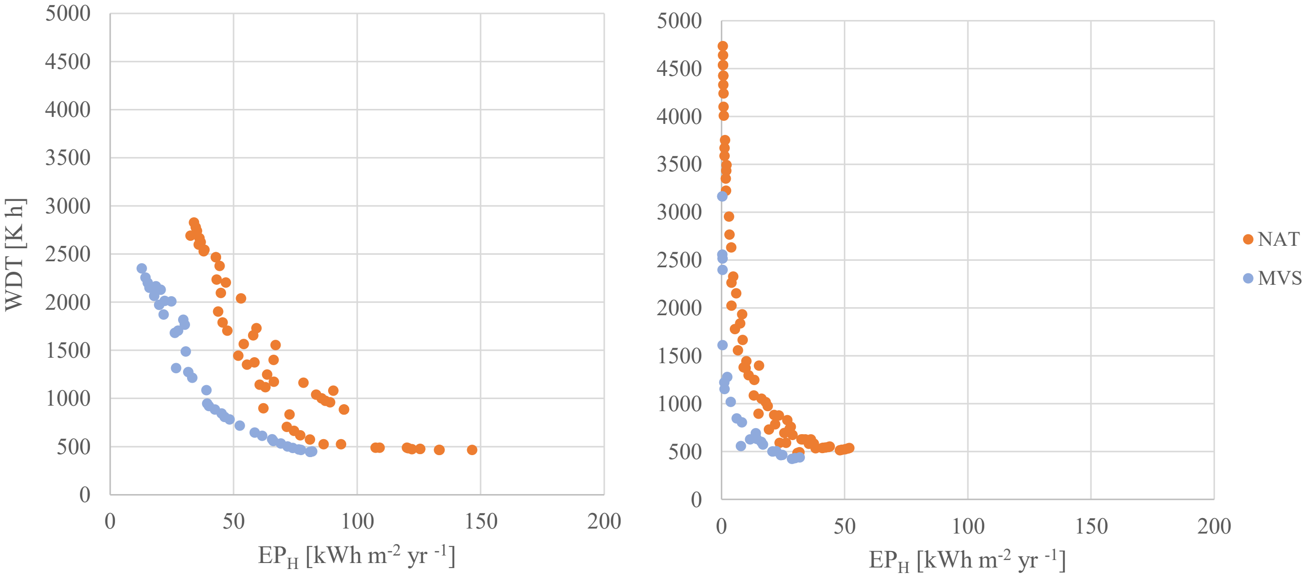


Figure 5 Pareto surfaces plotted on EPH and NPV diagram for the case REF 1, windows south oriented, S/V=0.97 located in Milan and S/V=0.63 in Messina. The two graphs on the top report the Pareto-solutions according to different types of windows, the two graphs on the bottom according to the presence of mechanical ventilation system.

REF 1 - SOUTH (EP$_H$-WDT)


MILANO

MESSINA


WDT [K h]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
EP_H [kWh m^{-2} yr^{-1}]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
EP_H [kWh m^{-2} yr^{-1}]
● NAT
● MVS