Robustness of multi-objective optimization of building refurbishment to suboptimal weather data

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ABSTRACT

The interest in energy refurbishment has been growing in the last few years, since noticeable energy savings can be achieved through energy saving measures (*ESMs*) applied to the existing building stock. In this respect, one of the best opportunities to promote the energy renovation of the existing buildings is to define cost-effective solutions through multi-objective optimization techniques, which can rely on genetic algorithms (*GA*), and building energy simulation (*BES*). Although this topic has been widely discussed in the literature, little is yet known about the robustness of the optimal solutions obtained from *GA* multi-objective optimizations to the variation of the quality of the used weather data. This information could also be relevant to understand if the optimal solution obtained with historic weather data could be undermined by future climate changes. Aiming to provide objective confidence levels of the multi-objective optimization, in this work we investigate the extent to which the weather data used for *BES* can affect the optimal solutions. With this purpose, several multi-objective optimizations have been carried out with reference years obtained with different lengths of historic series for the location of Trento, North Italy. The results show changes to both Pareto's fronts and optimal *retrofit solution.*

1. INTRODUCTION

The European Directive 31/2010 (European Commission, 2010) and the Commission Delegated Regulation EU 244/2012 (European Commission, 2012) suggest the renovation of existing buildings into nearly zero-energy buildings and the definition of cost-optimal levels into the framework of building energy refurbishment. Among all possible *ESMs*, the designer should define the one that optimizes some competitive goals, such as the minimization of the net present value (*NPV*) and the minimization of primary energy (*EP*). For this reason, multi-objective optimization is often applied to *BES* to determine a set of equivalent optimal solutions, the so-called Pareto's front. Among the possible multi-objective optimization strategies, the evolutionary optimization approaches, such as the genetic algorithms, have become popular in research and application fields (Penna *et al.*, 2014).

A sensitive issue undermining the suitability of multi-objective optimization in finding cost optimal solutions deals with its robustness to imprecise input data. In this regard, while *GA* robustness to algorithm parameters has been widely investigated (Wright and Alajmi, 2005; Ihm and Krarti, 2012), little attention has been paid to the robustness to suboptimal inputs. In this framework, the representativeness of weather inputs is a key aspect to obtain reliable building simulation results. In fact, the length of the multi-year weather data series and the methodology used for the typical month selection largely influence the results of the reference year development process (Pernigotto *et al.*, 2014a; Pernigotto *et al.*, 2014b) and, consequently, could affect the cost optimal identification. Furthermore, *GA* robustness to weather data variability is also required in order to obtain optimal solutions, robust to climate changes.

In this work, we investigate the extent to which the weather data used for *BES* can affect the optimal solutions and, so, the robustness of *GA* approach for multi-objective optimization. With this purpose, several multi-objective optimizations have been carried out with different reference years, developed according to EN ISO 15927-4:2005 (CEN, 2005) from different sets of hourly weather data series collected in the meteorological station of Trento, in northern Italy (Pernigotto *et al.*, 2014b). Different building configurations are analyzed with the purpose of enhancing the conclusion's generality.

2. METHOD

The choice of optimal trade-off between energy savings and net present value is based on the domination of a general solution *X* over a solution *Y*. According to Pareto, *X* dominates *Y* if the following conditions are both true:

1. The solution *X* is no worse than *Y* in all objectives;
2. The solution *X* is strictly better than *Y* in at least one objective.

Thus, passing from *X* to *Y*, an improvement for all objectives – or at least for some of them, is supposed, without harming the other ones. When an objective cannot improve without making worse the others, we are considering an "Optimum of Pareto".

The two steps of the optimization procedure are therefore (a) the definition of Pareto's front and (b) the selection of a trade-off solution among those belonging to Pareto's front. For the multi-objective optimization of building retrofits, the chosen genetic algorithm is implemented in MatLab. The fitness function used in the analysis is a Matlab code that launches TRNSYS *BES*. After the model execution, the function reads TRNSYS output file and post-processes the simulation results. The code computes the *NPV* by means of the method proposed by the technical standard EN ISO 15459:2009 (CEN, 2009) and returns the two objectives to the genetic algorithm. In particular, *NPV* and *EP* for space-heating (EP_h) are chosen as goals for the multi-objective optimization.

2.1 Genetic algorithm implementation

The implemented genetic algorithm is *Elitist Non-dominated Sorting Genetic Algorithm, NSGA-II* (Deb, 2002), with some code customizations regarding sampling, crossover, mutation and selection procedures. These modifications, coupled with selection of mutation rate, population size and crossover fraction, are adopted with the purpose of increasing the genetic algorithm performances.

The first step is the selection of the initial population, to which the genetic algorithm optimization is closely related. In this regard, random sampling could lead to oversampling, whereas a uniform random number generation, such as Sobol's sequence, produces uniform sample when the population size is high (Saltelli *et al.*, 2004, Burhenne *et al.*, 2011). The random starting point in Sobol´s sequence is obtained through a pseudo random generator (Matsumoto and Nishimura, 1998).

Once the fitness function is evaluated, the genetic algorithm proceeds with the selection of the best individuals (i.e., the "parents" for the next generation). In this study, we adopt the *Tournament Selection Without Replacement* (Goldberg *et al.*, 1989, Golberg and Deb, 1991). In this method, a short list of four eligible parents is randomly chosen and the best individual among them is set to be a parent. Then, the code combines the genetic characteristics of both parents, giving rise to the new generation. Children are a random (Matsumoto and Nishimura, 1998) arithmetic mean of two parents, thus children are always feasible with respect to bounds (Burjorjee, 2013). The adopted crossover fraction, i.e., the fraction of the next generation that crosses over, is set equal to 0.8. The remaining individuals in the next generation come from population mutation. Mutation is applied at a random point in a random individual. In particular, by means of Mersenne-Twister pseudo random generator (Matsumoto and Nishimura, 1998), a randomly selected gene is replaced by a uniformly distributed random value that meets the gene range.

2.2 Test Cases

With the purpose of ensuring the analysis generalization, three typologies of building (Fig. 1) are investigated: semi-detached houses (S/V = 0.97 m^{-1}), penthouses (S/V = 0.63 m^{-1}) and intermediate flats in multi-story buildings (S/V = 0.3 m^{-1}). Each building has 100 m^2 of floor surface, 3 m of internal height and façades oriented towards the main cardinal directions. Adiabatic boundary conditions are imposed to model the adjacency to other buildings. Otherwise, the envelope surfaces are directly exposed to the external environment (without thermal contact with the ground for the semi-detached house floor). The considered configurations have windows only in one façade (east or south), which is also in front of the vertical wall adjacent to other buildings.

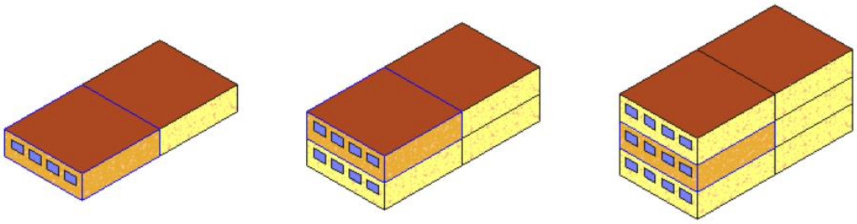

Figure 1: Building typologies used in the genetic algorithm procedure

The thermal transmittances of opaque and transparent components have typical values of the Italian building stock built before the first Italian energy saving law, law 373 of 1976 (Table 1). A simplified structure with a single massive layer of clay is considered for the opaque envelope and a single-pane glass is used for the glazing systems, with standard timber frame modelled with LBNL Window 6.3. The linear thermal transmittances of thermal bridges are computed according to EN ISO 10211:2007 (CEN, 2007a) by means of LBNL THERM 6.3 and the infiltration rates are estimated according to EN 12207:1999 (CEN, 1999) and EN 15242:2007 (CEN, 2007b). The reference air tightness n50 is 7 ACH and the associated infiltration rates for the three building typologies are reported in Table 1.

Table 1: Building characteristics

Opaque Envelope		**Windows**		**Infiltration Rate (ACH)**
d (m)	0.20	Glazing: Single-pane		Intermediate flat in multistory
λ (W m^{-1} K^{-1})	0.25	U_{gl} (W m^{-2} K^{-1})	5.69	0.06
R (m^2 K W^{-1})	0.80	$SHGC$	0.81	Semi-detached houses
κ (kJ m^{-2} K^{-1})	150	Frame: Standard Timber		0.13
ρ (kg m^{-3})	893	U_{fr} (W m^{-2} K^{-1})	3.20	Penthouses
c (J kg^{-1} K^{-1})	840	A_f/A_{win} (%)	19.9	0.20

Similarly, in order to model buildings built up to 1970s and not yet renovated, a standard boiler coupled with radiators and on-off system regulation are used.

2.3 Weather data

Representative weather information is essential for a reliable building energy performance evaluation. Therefore, a reference year should characterize the climatic conditions typical for the entire life cycle of the analyzed building. However, historic series of measured meteorological variables, which are sufficiently long to develop accurate reference years, are not available for many locations and this can lead to representativeness issues (Pernigotto *et al.*, 2014a; Pernigotto *et al.*, 2014b). In this work, we verify how the variability of weather data may affect the optimal retrofit solutions choice for the city of Trento, north of Italy (Köppen classification: Cfa; ASHRAE 196/2006 classification: 4A). The different lengths of historic series presented in (Pernigotto *et al.*, 2014b) are adopted, in order to consider series with different levels of weather data availability. The different choices of representative months produce a significant change in Heating Degree-Days (HDD_{18}) and in solar radiation as shown in Table 2. In particular, the maximum HDD_{18}, obtained with the series with seven years, is about 10 % larger than the average of the six cases and the minimum HDD_{18}, arising from the analysis of series with eight years, leads to an underestimation of about 13 % with respect to the average value.

Table 2: Heating Degree-Days with a base temperature of 18 °C and daily average global solar radiation on horizontal surface (*Isol*) obtained with different lengths of historical series

Length of series (yr)	10	9	8	7	6	5
HDD_{18} (K d)	2499	2674	2167	2759	2298	2657
$\Delta HDD_{18}/HDD_{18,\,avg}$	-0.40 %	6.58 %	-13.63 %	9.96 %	-8.41 %	5.90 %
$Isol$ (MJ m^{-2} day)	7.98	7.49	6.15	7.09	6.51	7.70
$\Delta Isol/Isol_{avg}$	11.5 %	4.7 %	-14.0 %	-0.8 %	-9.0 %	17.0 %

2.4 Energy saving measures and economic analysis

In the multi-objective optimization analysis, six different types of *ESMs* are evaluated. These measures are the most common solutions adopted by designers to reduce EP_h. The implemented strategies are:

- an additional insulating layer of extruded polystyrene (EPS) with a thermal conductivity of 0.04 W m^{-1} K^{-1} and possible thickness from 1 to 20 cm, applied to the external surface of:
    - non-adiabatic walls
    - ceiling (only for the semi-detached houses and penthouses)
    - floor (only for the semi-detached houses);
- replacement of existing windows with high performance frames and glazings (i.e., double or triple plane with either high or low solar heat gain coefficients);
- replacement of existing boiler with either modulating or condensing boiler. In both cases the new boiler is also equipped with an external climatic adjustment in order to vary the supply temperature as a function of the external air temperature;
- adding mechanical ventilation with heat recovery system.

In addition to these *ESMs*, the improvements associated with the proposed measures in the building envelope are assessed. In fact, the addition of the external insulation mitigates the thermal bridges and, consequently, reduces their linear thermal transmittance, recalculated according to the same approach explained before (Penna *et al.*, 2014). Besides, the windows replacements greatly reduce the air tightness and, thus, the building infiltration rate. In that regard, a 50 % reduction of the rate of infiltration has been associated with the replacement of windows. Although the boiler replacement is considered, the substitution of the emission and distribution systems were not treated since they are linked to a whole building refurbishment rather than an *ESM*. The prices adopted for the different *ESMs* (Table 3) are found in the official regional price list and the energy source prices come from the database of the national authority of gas and electricity. *NPVs* are computed to evaluate the economic objective of the multi-objective optimization as suggested by the regulation EU 244/2012 (European Commission, 2012). The length of the investment analysis is 30 years and we take into account the initial Investment Cost (*IC*), the annual running costs (composed by energy and maintenance costs), the replacement cost due to periodic substitution of building elements, and the residual value for the equipment with longer lifespan.

2.5 Building energy simulation

The other objective of the multi-objective optimization is the annual primary energy required to provide for building heating demand. EP_h is calculated by means of TRNSYS hourly simulation. Each building is modeled by means of TRNSYS Multizone Building subroutine, type 56. Besides, a full Reindl correlation (Reindl *et al.*, 1990) coupled with Perez projection model (Perez *et al.*, 1988) are used to compute the solar radiation incident to tilted surfaces. Type 869 (Haller *et al.*, 2011a; Haller *et al.*, 2011b) is adopted to model different heating systems since it is able to consider the behavior of either standard or modulating and condensing boiler. The heating system is controlled by an *on/off* thermostat (type 2) that switches *on* the boiler if the indoor air temperature is lower than 20 °C and switches *off* the boiler if the air temperature overcomes 22 °C. The pump power consumption is modeled by means of type 3 while type 31 is used to compute the distribution heat losses of pipes.

Table 3: Different *ESMs* considered in the genetic algorithm procedure

Additional Insulating Layer			
Thermal characteristic of Polystyrene EPS			**Cost (€ m^{-2})**
λ (W m^{-1} K^{-1})	c (J kg^{-1} K^{-1})	ρ (kg m^{-3})	IC_{VW} = 0.016·d + 38.53
0.04	1470	40	IC_{HW} = 0.0188·d + 8.19 d is the thickness (m)
Windows replacement			
Aluminum Frame with thermal break U_{fr} = 1.2 W m^{-2} K^{-1}			***IC* for windows**
Glazing	**U_{gl} (W m^{-2} K^{-1})**	***SHGC***	**Cost (€ m^{-2})**
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
Boiler replacement		**Mechanical ventilation system (*MVS*)**	
Standard (*Std*)	IC_{STD} = 1000 €	Ventilation Rate (m^3 h^{-1})	Power (W)
Modulating (*Mod*)	IC_{MOD} = 1500 €	150	59.7
Condensing (*Cond*)	IC_{COND} = 2000 €	IC_{MVS} = 6000 €	
Parameters for the economic analysis			
Fuel Cost	0.85 € Sm^{-3}	Electricity Cost	0.25 € kWh_{el}^{-1}
Lower Heating Value	32.724 MJ Sm^{-3}	Increase electricity price	1.71 %
Increase fuel price	2.8 %		
VAT	10 %	Real Interest Rate	3 %

3. RESULTS AND DISCUSSION

3.1 Pareto's Fronts

The different length of the historic series induces different trends in temperature and solar radiation by altering the selection of the representative months. Hence, the length of the series also causes in the initial building a variability of EP_h and, thus, of *NPV*. Initial EP_h and *NPV* evaluated with the reference year from the 10-year long series are reported in Tables 4 and 5. The configurations with east-faced windows have the largest EP_h and *NPV*, approximately around +35 kWh m^{-2} yr^{-1} and +9000 € with respect to the corresponding cases with windows on the south façade. The buildings with *S/V* equal to 0.97 m^{-1} have EP_h and *NPV* twice larger than those with *S/V* equal to 0.30 m^{-1}. Tables 4 and 5 show also the percentage deviations of the initial conditions according to the different reference years. The greatest differences are found for the reference year developed from the series with eight years for every building configuration.

Figure 2 reports the results of the optimization process according to the different *S/V* ratios and windows orientation. The charts show the trade-off between *NPV* and EP_h obtained with different reference years. In each, we can distinguish two groups: the optimal solutions with mechanical ventilation system (*MVS*) in the higher-left part of the diagram (i.e., with higher *NPVs* and lower EP_h) and those with natural ventilation in the lower-right part (i.e., with lower *NPVs* and higher EP_h).

Table 4: Percentage variation respect to 10 years base in EP_h, caused by different reference years

	Windows orientation	**10 years EP_h** [kWh m^{-2} yr^{-1}]	**9 years**	**8 years**	**7 years**	**6 years**	**5 years**
S/V = 0.30 m^{-1}	**East**	154.2	1.43 %	-4.76 %	2.02 %	-3.89 %	4.90 %
	South	119.7	0.35 %	-7.04 %	2.93 %	-2.62 %	4.22 %
S/V = 0.63 m^{-1}	**East**	240.9	0.79 %	-4.79 %	1.67 %	-2.93 %	3.89 %
	South	197.9	0.57 %	-5.38 %	2.63 %	-2.12 %	4.06 %
S/V = 0.97 m^{-1}	**East**	294.7	-2.48 %	-6.76 %	2.05 %	-6.64 %	1.05 %
	South	264.9	0.67 %	-3.96 %	2.82 %	-2.23 %	4.43 %

Table 5: Percentage variation respect to 10 years base in *NPV*, caused by different reference years

	Windows orientation	**10 years *NPV* [€]**	**9 years**	**8 years**	**7 years**	**6 years**	**5 years**
S/V = 0.30 m^{-1}	**East**	42 666	1.41 %	-4.69 %	1.99 %	-3.83 %	4.82 %
	South	33 283	0.35 %	-6.89 %	2.87 %	-2.57 %	4.14 %
S/V = 0.63 m^{-1}	**East**	63 828	0.79 %	-4.74 %	1.65 %	-2.90 %	3.84 %
	South	54 553	0.57 %	-5.31 %	2.60 %	-2.10 %	4.01 %
S/V = 0.97 m^{-1}	**East**	80 911	-2.46 %	-6.70 %	2.03 %	-6.58 %	1.04 %
	South	72 817	0.66 %	-3.92 %	2.80 %	-2.21 %	4.39 %

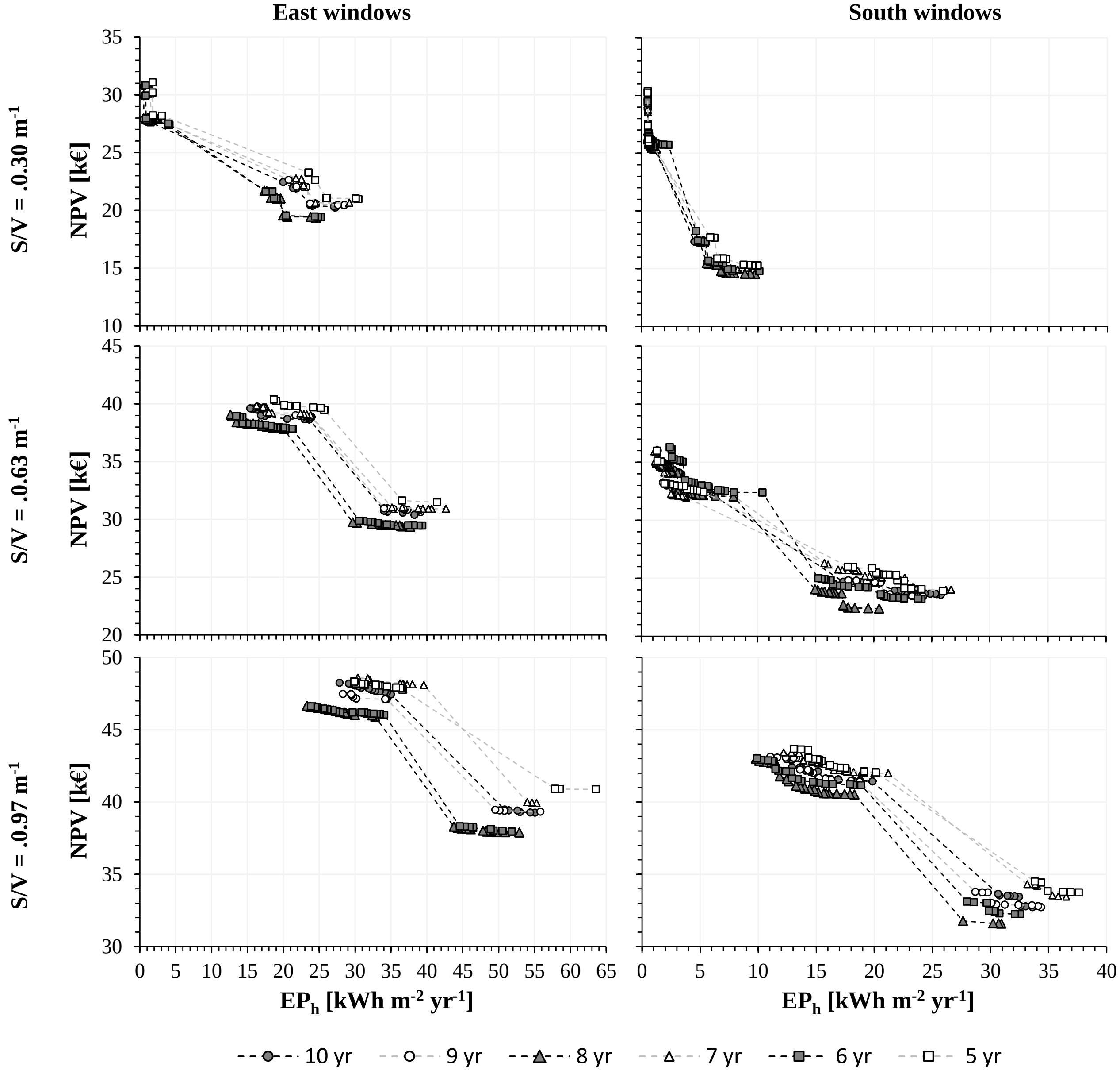

Figure 2: Pareto's fronts obtained for the different building configurations

Analyzing the optimized results, we can see that in building configurations with higher heating needs the reduction of *NPV*, with respect to the initial case, and thus the economic efficiency of the different *ESMs*, are larger than the other cases.

The variability of climatic conditions is also reflected in a shift of Pareto's fronts. In some cases, there are intersections of Pareto's curves obtained for different reference years: the translation in Pareto's fronts obtained with series of different lengths is not equal in buildings with natural or mechanical ventilation. For instance, in the case of *S/V* equal to 0.63 m^{-1} with windows facing south, considering the group of configurations with natural ventilation, the Pareto's front with highest *NPV* and EP_h is obtained with the reference year developed from the series with five years, whereas one of the lowest is that of the reference year from the series with six years. In the chart area of solutions with mechanical ventilation systems, however, a different behavior is noted and the highest curves become the front of the reference years from the series with six years. The fronts are not simply moved but they consider also different non-dominated solutions. The variability of the climate influences the choice of the optimal solutions.

3.2 Cost optimal

In order to evaluate in detail the effects of the different reference years on the optimal solution, we analyze the *ESM* configurations ensuring the minimum of a single objective. This analysis allows to highlight the possibility that the optimal solution is achieved with a different *ESMs* for the same building typology, depending on weather data used for calculation.

The analysis of the optimal configurations, in terms of minimum *NPV*, clearly shows that the natural ventilation is always the most favorable solution (Table 6). Similarly, the replacement of the existing window with *DH* glazing systems always allows the minimization of the total cost during the building life cycle. The only exception is the semi-detached house with east oriented windows when the reference year developed from seven years is adopted. In this case, the minimum *NPV* is ensured with *TH* windows.

Table 6: Optimal solutions in reducing *NPV*

	East windows orientation						**South windows orientation**					
	Insulation thickness [cm]			**Win**	**Boiler**	**Ven**	**Insulation thickness [cm]**			**Win**	**Boiler**	**Ven**
	Wall	**Roof**	**Floor**				**Wall**	**Roof**	**Floor**			
Intermediate flat in multi-story buildings *S/V* = 0.30 m^{-1}												
10 yr	19	0	0	DH	Std	Nat	17	0	0	DH	Std	Nat
9 yr	18	0	0	DH	Std	Nat	18	0	0	DH	Std	Nat
8 yr	18	0	0	DH	Std	Nat	12	0	0	DH	Std	Nat
7 yr	18	0	0	DH	Std	Nat	18	0	0	DH	Std	Nat
6 yr	17	0	0	DH	Std	Nat	13	0	0	DH	Std	Nat
5 yr	18	0	0	DH	Std	Nat	17	0	0	DH	Std	Nat
Penthouse *S/V* = 0.63 m^{-1}												
10 yr	18	17	0	DH	Cond	Nat	17	15	0	DH	Std	Nat
9 yr	18	17	0	DH	Cond	Nat	19	15	0	DH	Std	Nat
8 yr	18	17	0	DH	Mod	Nat	19	15	0	DH	Std	Nat
7 yr	16	15	0	DH	Cond	Nat	17	16	0	DH	Std	Nat
6 yr	17	16	0	DH	Mod	Nat	16	16	0	DH	Std	Nat
5 yr	18	18	0	DH	Cond	Nat	16	17	0	DH	Std	Nat
Semi-detached houses *S/V* = 0.97 m^{-1}												
10 yr	19	19	18	DH	Mod	Nat	17	18	17	DH	Mod	Nat
9 yr	16	17	17	DH	Cond	Nat	17	17	17	DH	Mod	Nat
8 yr	16	15	16	DH	Cond	Nat	17	16	17	DH	Mod	Nat
7 yr	18	18	17	TH	Mod	Nat	18	17	17	DH	Mod	Nat
6 yr	17	17	15	DH	Cond	Nat	17	17	17	DH	Mod	Nat
5 yr	17	18	17	DH	Mod	Nat	18	16	18	DH	Mod	Nat

A greater variability is found in the optimal insulation levels and in the boiler replacement. For the latter, in fact, the reference year greatly affects the choice of the new boiler, except for the intermediate flat in multi-story buildings and for the penthouse with south oriented windows, for which the boiler replacement is never convenient.

3.3 Energy performance optimal

The optimal EP_h configurations present different results (Table 7). The insulation thickness is generally equal or close to the maximum allowable (i.e., 20 cm) with the exception of the building with S/V = 0.3 m^{-1} and south oriented windows, whose optimal insulation switches from 13 cm (reference years from series with eight, nine or ten years) to 20 cm (reference years from series with six years). The original windows are always changed with triple-pane glazing systems: they are always *TH*, excluding the intermediate flats with windows on the south façade, for which *TL* are preferred when the reference years are developed starting from series with less than eight years. As regards the boiler, the condensing one is the prevalent optimal solution. No boiler replacement is suggested for the buildings with S/V = 0.3 m^{-1} when evaluated with 9 and 8-year series reference years while for the penthouse a modulating boiler is recommended when the weather file comes from the 9-year series. The mechanical ventilation system is adopted whatever the building configuration and the weather file.

Table 7: Optimal solutions in reducing EP_h

	East windows orientation						**South windows orientation**					
	Insulation thickness [cm]			**Win**	**Boiler**	**Ven**	**Insulation thickness [cm]**			**Win**	**Boiler**	**Ven**
	Wall	**Roof**	**Floor**				**Wall**	**Roof**	**Floor**			
Intermediate flat in multi-story buildings S/V = 0.30 m^{-1}												
10 yr	20	0	0	TH	Cond	MVS	13	0	0	TH	Cond	MVS
9 yr	20	0	0	TH	Std	MVS	13	0	0	TH	Std	MVS
8 yr	20	0	0	TH	Std	MVS	13	0	0	TH	Std	MVS
7 yr	20	0	0	TH	Cond	MVS	15	0	0	TL	Cond	MVS
6 yr	20	0	0	TH	Cond	MVS	20	0	0	TL	Cond	MVS
5 yr	20	0	0	TH	Cond	MVS	19	0	0	TL	Cond	MVS
Penthouse S/V = 0.63 m^{-1}												
10 yr	20	19	0	TH	Cond	MVS	20	20	0	TH	Cond	MVS
9 yr	19	19	0	TH	Cond	MVS	20	20	0	TH	Mod	MVS
8 yr	20	20	0	TH	Cond	MVS	20	20	0	TH	Cond	MVS
7 yr	20	19	0	TH	Cond	MVS	20	20	0	TH	Cond	MVS
6 yr	19	19	0	TH	Cond	MVS	20	20	0	TH	Cond	MVS
5 yr	19	19	0	TH	Cond	MVS	20	20	0	TH	Cond	MVS
Semi-detached houses S/V = 0.97 m^{-1}												
10 yr	20	20	20	TH	Cond	MVS	19	19	18	TH	Cond	MVS
9 yr	18	18	19	TH	Cond	MVS	19	19	19	TH	Cond	MVS
8 yr	19	19	20	TH	Cond	MVS	19	20	19	TH	Cond	MVS
7 yr	19	20	19	TH	Cond	MVS	19	19	19	TH	Cond	MVS
6 yr	19	19	19	TH	Cond	MVS	19	19	20	TH	Cond	MVS
5 yr	18	20	19	TH	Cond	MVS	19	19	19	TH	Cond	MVS

4. CONCLUSIONS

In this work, we assessed the robustness of a genetic algorithm, the *Elitist Non-dominated Sorting Genetic Algorithm*, used for multi-objective optimizations in building energy refurbishment to suboptimal hourly weather data. In particular, we focused on the reference years developed according to EN ISO 15927-4:2005 and on the lack of sufficiently long historic weather series of hourly dry bulb temperature, relative humidity, horizontal global radiation and wind speed data. We developed some reference years starting from series of different length – from five to ten years of collected measurements, for the location of Trento, north Italy. These reference years were used as inputs for the refurbishment multi-objective optimization of six buildings with three possible ratios between the externally exposed surface and the conditioned volume and two alternatives of windows orientations. Among the available energy saving measures for the reduction of final uses for space heating, we considered wall insulation, windows and boiler substitutions and installation of a mechanical ventilation system with heat recovery. The optimization involved the trade-off between final energy uses for space heating and the net present value, which were investigated in terms of Pareto's fronts. Since each reference year gives specific initial conditions of EP_h and *NPV*, different Pareto's fronts are found for each building configuration. The results show that fronts are not simply shifted on the NPV-EP_h chart but, in some cases, they can have different shapes, leading to different optimal solutions. The actual choice of the optimal *ESM* in Pareto's front depends on the weights given to the objectives in trade-off. In order to analyze which *ESMs* are more sensitive to the weather data input, we performed two separate studies aimed at looking for (a) the *ESM* that optimizes the *NPV* and (b) the one optimizing the EP_h among those on Pareto's fronts. We found different sensitivities according to the building kind but, in general, the insulation level and the boiler replacement have the largest variability, which is more emphasized in the *NPV* optimization context. The selection of the best solution for window substitution is more robust to the weather inputs. As regards the ventilation, there is no sensitivity at all for the considered buildings.

The results of this study demonstrate that when some representativeness issues are present in the reference years, different optimal *ESMs* are highlighted by the multi-objective optimization. This finding stresses, once more, the importance of reliable and representative weather data in *BES*. Moreover, the optimization process is projected in a future period while the typicality of the reference year is evaluated with respect to the past. The reference year does not take into account at all the future dynamics of possible climate changes and, so, the optimization can be wrong in actual future scenarios. Since reliable weather inputs for climate changes are hard to estimate, the resilience to external inputs should be a target to pursue in the multi-objective optimization for building refurbishment.

NOMENCLATURE

A	surface	(m^2)
c	specific heat	($J\ kg^{-1}\ K^{-1}$)
d	thickness	(m)
EP	primary energy	($kWh\ m^{-2}\ yr^{-1}$)
HDD	heating degree days	(K day)
I	solar irradiance	($MJ\ m^{-2}$)
IC	initial cost	(€)
λ	thermal conductivity	($W\ m^{-1}\ K^{-1}$)
κ	thermal capacitance	($J\ m^{-2}\ K^{-1}$)
NPV	net present value	(€)
R	thermal resistance	($m^2\ K\ W^{-1}$)
ρ	specific mass	($kg\ m^{-3}$)
S	envelope exposed surface	(m^2)
$SHGC$	solar heat gain coefficient	(-)
U	thermal transmittance	($W\ m^{-2}K^{-1}$)
V	conditioned volume	(m^3)

Subscript

avg	average respect to the five reference years
f	floor
fr	frame
gl	glazing
h	heating
hw	horizontal element
sol	solar
vw	vertical wall
w	window

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