

Robustness of multi-objective optimization of building refurbishment to solar radiation model

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Abstract

The energy saving potential of existing buildings in highly urbanized world areas stimulates interest in the introduction of renovation measures. Due to the high economic impact of those interventions, special attention has to be paid to balance energy and economic performance, leading to the definition of the best combination through multi-objective approach. The recourse to building simulation, to improve the resolution and discrimination capability between different renovation configurations, forces us to consider the quality of the input data and leads to robustness issues for the optimal solution. In this regard, a reliable estimation of the global irradiation incident on various tilted surfaces is essential in order to account for the solar heat gains. Nonetheless, many meteorological stations monitor only global solar radiation on a horizontal plane. As a consequence, a variety of mathematical and empirical models have been proposed in the literature for both the subdivision of horizontal solar irradiation into direct and diffuse components and for the calculation of irradiation on tilted surfaces. Besides introducing inter-model uncertainty, no pair of diffuse and tilt irradiation models can provide results with the same reliability for worldwide localities different from those considered for the definition of each model.

This research work investigates the extent to which the choice of solar irradiation models affects the confidence levels of the optimal solutions provided by multi-objective optimizations. With this purpose, several multi-objective optimizations are carried out with different solar irradiation models. Semi-detached houses, penthouses and intermediate flat in multi-storey buildings are analyzed with the purpose of broadening the representativeness of the conclusions.

1. Introduction

A careful design of new buildings and building renovation can provide high energy savings. However, since new buildings represent a small amount of the whole construction activities, the interest in optimizing building renovation has greatly increased in the last few years.

Moreover, the coming into force of the Directive 31/2010 (European Commission, 2010), and the Commission Delegated Regulation EU 244/2012 (European Commission, 2012) highlights the necessity to consider the cost-optimal levels in the framework of the building energy refurbishments.

For this reason, the minimization of net present value (*NPV*) and of the achievable energy performance index (*EP*) are often used among many possible goals for the selection of the optimal mix of energy saving measures (*ESMs*). However, the extensive evaluation of all possible combinations of *ESMs* through a full factorial plan can be extremely time consuming and difficult to handle. The application of multi-objective optimization techniques (*MOO*), such as those based on the genetic algorithm (*GA*), can overcome this problem, ensuring a greater reduction of the computational time.

However, the suitability of *MOO* in finding optimal solutions has to deal with their robustness to imprecise input data. In fact, the higher capabilities of hourly simulation codes imply more complex and detailed inputs. In this regard, while *GA* robustness to algorithm parameters have been widely investigated (Wright and Alajmi, 2005; Ihm and Krarti, 2012), little attention has been paid to imprecise input (Prada *et al.* 2014a).

In this framework, the representativeness of solar irradiation data assumes relevance in building simulation results, especially in nearly-zero energy buildings (*nZEB*), which rely on solar irradiation for reducing the heating demand (Prada *et al.*, 2014b). The reliability of numerical models used in the pre-processing of solar data is a key aspect, since most of the meteorological stations monitor only global solar irradiation on a horizontal plane. Hence, a variety of mathematical and empirical models has been proposed in the literature (Prada *et al.*, 2015) for both the subdivision of horizontal solar irradiation into direct and diffuse components (*horizontal diffuse irradiance models*) and for the calculation of irradiation on tilted surfaces (*irradiance models for tilted surfaces*). Moreover, models can hardly provide results with the same reliability for localities different from those in which they have been derived. Therefore, the choice of the couple of solar irradiation models can greatly affect the reliability of the building energy simulation (Prada *et al.*, 2014b).

The aim of this work is to investigate the robustness of the NSGA II procedure (Deb *et al.*, 2002) in finding optimal *ESMs* in building energy renovation when different solar irradiation models are used. *MOO* has been repeated with three relevant couples of models, chosen from the entire population of 264 combinations studied in (Prada *et al.*, 2015) for three kind of buildings, in the climate of Rome.

2. Methods

2.1 Case of study

Three building typologies are investigated (Fig. 1) with the purpose of generalizing the main findings. In particular, semi-detached houses ($S/V = 0.97 \text{ m}^{-1}$), penthouses ($S/V = 0.63 \text{ m}^{-1}$) and intermediate flats in multi-story buildings ($S/V = 0.3 \text{ m}^{-1}$) have been considered. These buildings were developed starting from a reference building module, which is a typical flat having 100 m^2 floor surface, 3 m internal height and façades oriented towards the main cardinal directions. The floor area is consistent with the weighted average surface of the

European residential buildings (UNECE, 2006) and the other characteristics derived from the screening analysis (Pernigotto *et al.*, 2014). Windows are all in the same façade and the window to floor ratio is equal to 0.144. Either a south or an east windows orientation is considered. As a whole, 12 alternative configurations are considered for *MOO*. An adiabatic boundary condition is imposed when the envelope structures are adjacent to other buildings. In all the other cases, the surfaces are directly exposed to the external environment.

Two alternatives of opaque envelope are modelled: *REF 1*, representative of constructions built prior to the first Italian energy law in 1976 (Italian Parliament 1976), has a thermal resistance of $0.97 \text{ m}^2 \text{ K W}^{-1}$ while *REF 2*, representative of constructions built before the second energy legislations (Italian Parliament 1991), has a thermal resistance of $2.04 \text{ m}^2 \text{ K W}^{-1}$. Windows have a single pane glass with thermal transmittance of $5.7 \text{ W m}^{-2} \text{ K}^{-1}$ and SHGC of 0.81 and standard timber frame with thermal transmittance of $3.2 \text{ W m}^{-2} \text{ K}^{-1}$ and a projected area equal to 19.9 % of the whole window area.

The infiltration rate is estimated according to EN 12207 (CEN, 1999) and EN 15242 (CEN, 2007a). The reference air tightness n_{50} is 7 ACH and the associated infiltration rates are 0.20 ACH, 0.13 ACH and 0.062 ACH, respectively for semi-detached houses, penthouses and intermediate flats. Similarly, the heating system is a standard gas boiler coupled with radiators and on-off system control are used.

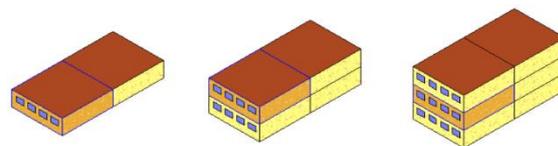


Fig. 1 – Test cases used in GA optimization.

2.2 Energy Saving Measures

The optimal mix of *ESMs* comes from the trade-off between energy performance for heating EP_h and NPV , according to the EN ISO 15459:2007 (CEN, 2007b). For this scope, an Elitist Non-dominated sorting *GA* algorithm, NSGA-II, (Deb 2002) was implemented in Matlab. The fitness function used in the analysis is a Matlab code that launches the

building energy simulation (i.e., TRNSYS model) and reads TRNSYS output file. Following on from this point, the code computes the *NPV* by means of the method proposed by the technical standard EN ISO 15459:2007 and it returns the two objectives to the NSGA-II algorithm. In particular, *NPV* and EP_h are chosen as goals for the multi-objective optimization.

We evaluated conventional *ESMs*, applied both to the envelope components and to the heating and ventilation system (Penna *et al.*, 2015):

1. external insulation of the opaque envelope with an EPS layer (thermal conductivity of $0.04 \text{ W m}^{-1} \text{ K}^{-1}$, specific heat of $1470 \text{ J kg}^{-1} \text{ K}^{-1}$ and density of 40 kg m^{-3}) in a range of thicknesses between 0 and 20 cm. The insulation thickness is changed differently for vertical walls, roof and floor and different installation costs are considered;
2. replacement of existing windows with four higher performance glazing systems (i.e. double or triple pane with either high or low SHGC) with improved aluminum frames with thermal break, whose thermal transmittance is $1.2 \text{ W m}^{-2} \text{ K}^{-1}$;
3. substitution of the heating boiler with either modulating or condensing boiler both with a climatic control adjustment;
4. installation of a mechanical ventilation system *MVS* with a cross flow heat recovery system.

Furthermore, some secondary energy performance improvements induced by the primary *ESMs* are considered:

1. the effects of thermal bridges are reduced depending on the insulation thickness and on window typology. The linear thermal transmittances have been computed using the polynomial regressions derived in (Penna *et al.*, 2015);
2. the infiltration rate is reduced with the installation of new windows. Hence, the infiltration rate is considered as a half of the starting values;
3. since the radiators are not changed, the decreasing heating needs allows reducing the emission power. Thus, when the boiler is replaced, the use of the climatic control allows the variation of the hot water supply temperatures and, consequently, the reduction of the distribution losses.

2.3 Solar radiation models

The hourly distributions of 264 couples of models presented in Prada *et al.* (2015) have been investigated for the city of Rome in order to select three representative couples of models. The predicted solar irradiations on vertical surfaces oriented towards the four cardinal points are computed and, for each hour, the results obtained by means of different models are sorted in ascending order. Then, the three pairs of models that more often fall in the first 66 positions (i.e., within the first quartile), in the last 66 positions (i.e., beyond the third quartile), and between first and third quartiles are chosen.

These models (Tab. 1) are considered representative of the average and extreme behaviors of the entire population, as highlights in Fig. 2.

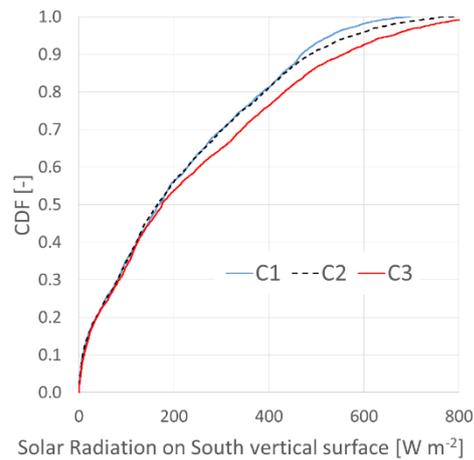


Fig. 2 – Cumulative distribution functions of the hourly solar irradiation with the three model combinations.

Table 1 – Solar irradiation models.

Combination	Horizontal Diffuse Irradiance models	Irradiance models for tilted surface
C1	Perez <i>et al.</i> 1992	Liu and Jordan 1960
C2	Boland <i>et al.</i> 2008	Burgler 1977
C3	Erbs <i>et al.</i> 1982	Perez <i>et al.</i> 1990

2.3.2 Horizontal diffuse irradiance models

The selected diffuse irradiance models have different characteristics. The older works, i.e., Erbs *et al.* (1982), correlate the diffuse fraction of solar irradiation with the clearness index that represents the portion of horizontal extraterrestrial radiation reaching the surface. Erbs *et al.* (1982) developed a regression model using a dataset of 65 months covering five locations over the U.S. On the contrary, Perez *et al.* (1992) proposed a modification to the DISC model proposed by Maxwell (1987). In particular, the modification dealt with the dynamics effect in time series. Besides, the authors introduced a new parameterization by using the weather data collected for several locations. The last model, proposed by Boland *et al.* (2008), involved a logistic function instead of piecewise linear or simple nonlinear functions.

2.3.3 Irradiance models for tilted surface

The model for the evaluation of solar irradiation on tilted surface in the first couple was developed by Liu and Jordan (1960). They assumed an isotropic behavior of the sky and, consequently, the diffuse irradiation can be evaluated using trigonometric relations. On the contrary, Bugler (1977) observed both an increased intensity of diffuse irradiation near the horizon and in the circumsolar region of the sky. Therefore, he introduced two corrective coefficients. The last selected model is the one proposed by Perez *et al.* (1990). In this work, the authors defined a model based on a subdivision of the sky diffuse irradiance in three components, i.e., the horizon brightness, the isotropic and the circumsolar irradiation. All the models cited in the previous paragraphs were implemented and combined in a Matlab code.

3. Results and discussions

The first result that we want to focus on is the effect of irradiation models on the annual energy performance (EP) of the not-renovated buildings. In particular, Table 2 presents the percentage

variation with respect to the C2 couple of models and its EP values. In most of the cases, the variations are in the range of $\pm 3\%$ but higher values larger than 10% are noted for compact buildings (i.e. $S/V=0.30\text{ m}^{-1}$ or $S/V=0.63\text{ m}^{-1}$) with south-faced windows. For those buildings, the energy balance is more related to solar heat gains, thus the variability of incident solar irradiation has a greater weight on the needs. This result is an indication of the level of robustness of dynamic simulation to the epistemic uncertainty introduced by the choice of solar irradiation models.

Starting from these results, the effect of the solar irradiation models on the Pareto's front is investigated. Figure 3 presents the different Pareto's fronts obtained with the three couples of irradiation models according to the S/V ratios and windows orientation for the REF 2 case. Similar results have been obtained also for the REF 1 buildings. In the trade-off between NPV and EP, there are two groups: the solutions with mechanical ventilation system (MVS) in the higher left-hand side and those with natural ventilation (NAT) in the lower right-hand side. In buildings with low heating needs, such as the intermediate flat in multi-storey buildings, the choice of solar irradiation models seems to affect scarcely the Pareto's front.

Due to the low EP in renovated compact buildings, the incident solar irradiation is much greater than the solar gains exploitable to reduce the limited heat losses. For this reason, the choice of the solar models have a weak impact on predicted heating needs. Larger differences are evident in the less compact buildings. A shift of Pareto's fronts is the primary effect of the different solar irradiation models. Although there are a few intersections in Pareto's curves obtained with the three couples of models, the choice of models alters the number of optimal solutions in the Pareto's front.

This is more evident in the less compact buildings with East oriented windows. For these buildings, the graphs show a different number of non-dominated solutions in the three fronts obtained with C1, C2 and C3.

Table 2 – Variation ΔEP [%] in the initial EP [kWh m^{-2}] of the reference cases. The subscripts referred to the model combinations

S/V	REF 1			REF 2			
	EP_2	ΔEP_{1-2}	ΔEP_{3-2}	EP_2	ΔEP_{1-2}	ΔEP_{3-2}	
0.3	East	76.1	-2.2	-0.9	57.1	-2.6	-1.3
	South	61.8	3.3	-9.5	44.1	4.7	-11.8
0.63	East	122.1	-2.1	0.0	105.3	-2.3	0.0
	South	107.9	0.9	-4.9	92.7	0.9	-5.0
0.97	East	169.2	-1.6	0.0	151.9	-1.5	0.1
	South	155.4	0.6	-3.4	139.8	0.8	-3.2

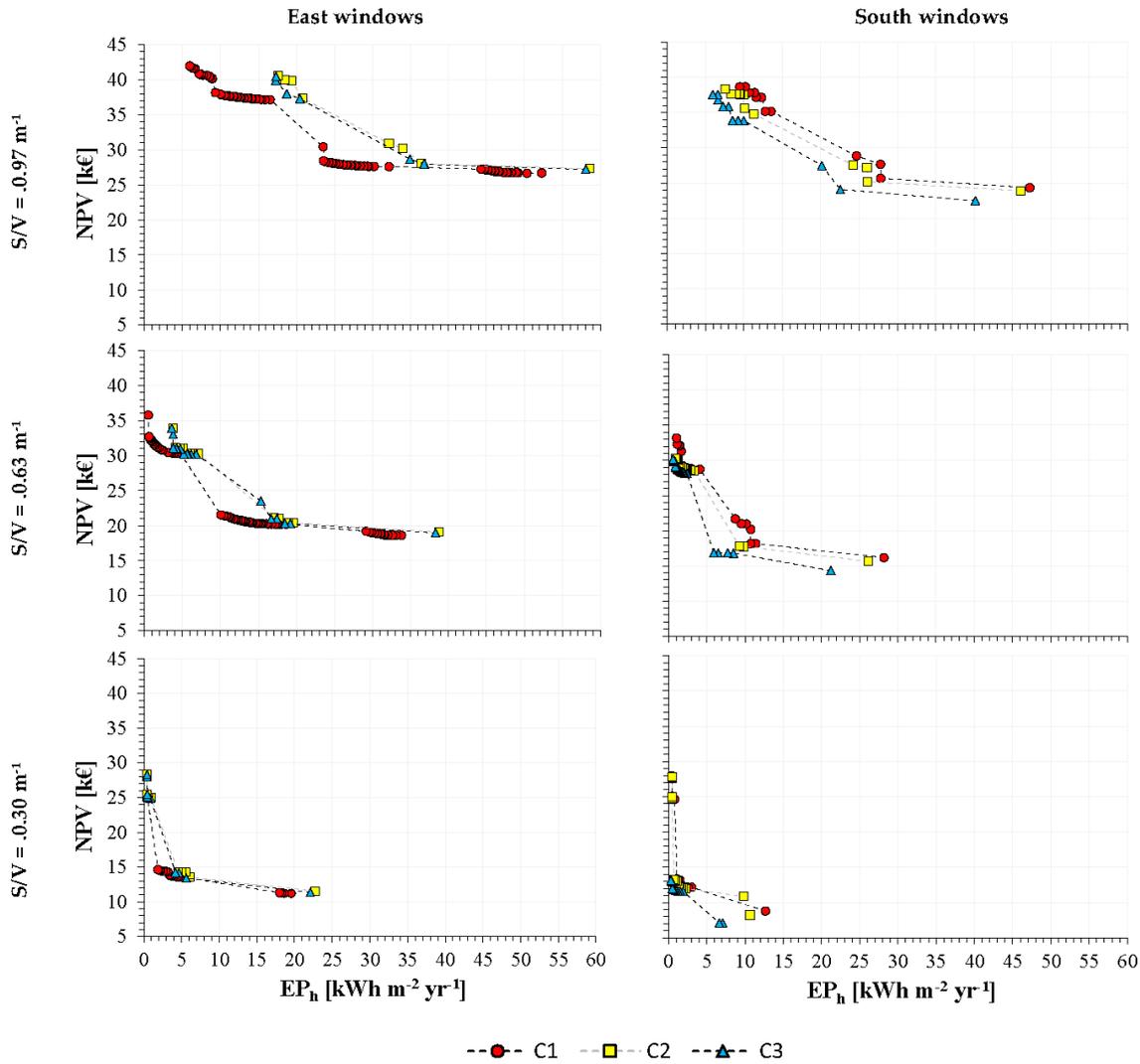


Fig. 3 – Pareto Fronts of the REF 2 cases

In particular, there are more optimal solutions in the front obtained with the combination C1. The additional solutions in C1 fronts are characterized by a greater insulation thickness for both walls and roof, and often by the replacement of windows with triple glazing with high SHGC. (TH) In fact, the

effectiveness of ESMs related to lower heat losses through the envelope increases since the C1 combination is characterized by lower solar irradiation on vertical surfaces. In the other combinations, however, these solutions are dominated by other retrofit solutions.

3.1 ESMs of Energy and Cost Optima

The mix of ESMs ensuring the minimum of a single objective are investigated in order to evaluate the effects of the different solar irradiation models.

Table 3 shows how the use of C1 induces an underestimation of solar gains, especially on east façades, thus making higher insulation thickness more economically advantageous. This is less

emphasized for buildings with windows facing south, since higher solar gains tend to reduce the effect. Table 4 also shows that only ESMs dealing with the opaque envelope are present in the retrofit solution ensuring the cost optimal retrofit due to the mild climate investigated. Similar behaviors are shown also for ESMs able to minimize the energy requirements of the buildings analyzed (Tab 4).

Table 3 – Combination of ESMs ensuring the minimum NPV for the REF 2 buildings.

	EST windows orientation						South windows orientation					
	Insulation thickness [cm]			Win code	Boiler code	Ventil. code	Insulation thickness [cm]			Win code	Boiler code	Ventil. code
	Wall	Roof	Floor				Wall	Roof	Floor			
Intermediate flat in multi-story buildings S/V=0.30 m⁻¹												
C1	15	-	-	SG	STD	NAT	11	-	-	SG	STD	NAT
C2	11	-	-	SG	STD	NAT	11	-	-	SG	STD	NAT
C3	11	-	-	SG	STD	NAT	10	-	-	SG	STD	NAT
Penthouse S/V=0.63 m⁻¹												
C1	16	12	-	SG	STD	NAT	11	11	-	SG	STD	NAT
C2	11	11	-	SG	STD	NAT	11	11	-	SG	STD	NAT
C3	11	11	-	SG	STD	NAT	11	11	-	SG	STD	NAT
Semi-detached houses S/V=0.97 m⁻¹												
C1	15	11	12	SG	STD	NAT	11	10	11	SG	STD	NAT
C2	10	10	11	SG	STD	NAT	10	10	11	SG	STD	NAT
C3	10	10	11	SG	STD	NAT	10	11	11	SG	STD	NAT

Table 4 – Combination of ESMs ensuring the minimum EP for the REF 2 buildings

	EST windows orientation						South windows orientation					
	Insulation thickness [cm]			Win code	Boiler code	Ventil. code	Insulation thickness [cm]			Win code	Boiler code	Ventil. code
	Wall	Roof	Floor				Wall	Roof	Floor			
Intermediate flat in multi-story buildings S/V=0.30 m⁻¹												
C1	11	-	-	DH	COND	MVS	8	-	-	DH	COND	VMC
C2	11	-	-	DH	COND	MVS	7	-	-	DH	COND	VMC
C3	11	-	-	DH	COND	MVS	12	-	-	TH	STD	NAT
Penthouse S/V=0.63 m⁻¹												
C1	20	20	-	TH	COND	MVS	12	12	-	TH	COND	VMC
C2	12	12	-	TH	COND	MVS	12	12	-	TH	STD	VMC
C3	12	12	-	TH	COND	MVS	12	12	-	TH	STD	VMC
Semi-detached houses S/V=0.97 m⁻¹												
C1	19	19	20	TH	COND	MVS	12	11	12	TH	COND	VMC
C2	11	11	11	TH	COND	MVS	12	12	12	TH	COND	VMC
C3	11	11	11	TH	COND	MVS	11	11	12	TH	COND	VMC

The measures minimizing the consumed primary energy involve the windows' replacement and the use of advanced and more efficient energy systems.

However, the choice of the solar models has a greater effect almost exclusively on the insulation thicknesses, especially in buildings with east oriented windows when C1 is used.

3.2 Comfort variations in Pareto's solutions

The previous paragraphs show a good robustness of the MOO method to the epistemic uncertainty introduced by the choice of solar models. However, substantial differences can be highlighted when assessing the comfort performance. The thermal comfort indicator used for the investigation is the discomfort weighted time (WDT) index, as proposed by the EN 15251 (CEN, 2007c) through the degree hours criteria. The graph in Fig. 4 clearly shows the WDT variations of REF1 semi-detached house caused by the choice of the models when NPV and EP are chosen as objectives. This greater sensitivity of WDT to solar models has repercussions on the robustness of MOO procedure when three different goals such as NPV, EP and WDT are considered. The Pareto's fronts in Fig. 5 show a greater dispersion of the results obtained with the three different combinations of solar models. In this case, therefore, the choice of a combination of models leads to the selection of different optimal mix of ESMs.

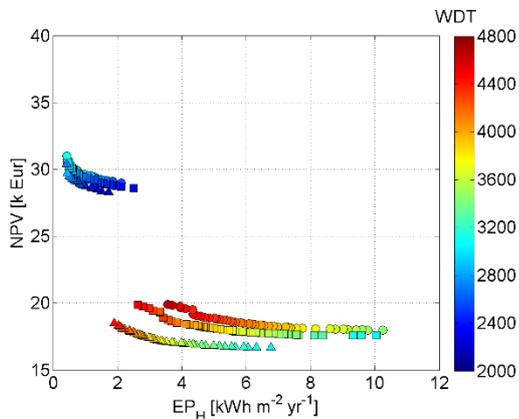


Fig. 4 – Pareto's fronts of the semi-detached house REF 1 with south oriented windows. The data points are colored according to WDT while circle referred to C1, square to C2 and triangle to C3.

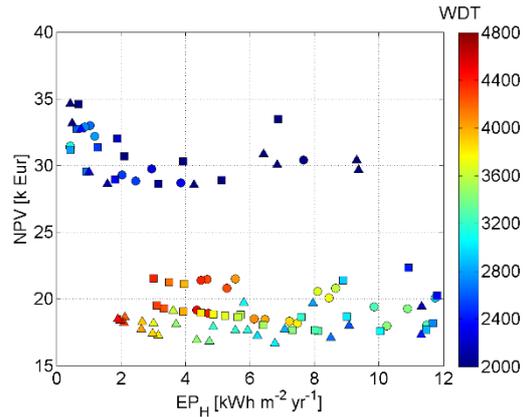


Fig. 5 – Pareto's fronts of the semi-detached house REF 1 with south oriented windows obtained with a 3 objective optimization. The data points are colored according to WDT while circle referred to C1, square to C2 and triangle to C3.

4. Conclusion

This work assessed the robustness of NSGA II in finding optimal building energy refurbishment when three different couples of solar irradiation models are adopted. The results show the variability of the EP index in the range of $\pm 3\%$ for most of the test cases for the simulation performed on the initial state.

As regards Pareto's fronts, the utilization of the C1 models makes some solutions not-dominated instead of dominated as they are for in cases C2 and C3. In particular, these new optimal solutions have higher insulation thickness and triple glazings due to the lower incident solar irradiation provided by C1 models.

Notice that slight differences are present in the mix of ESMs able to guarantee either the minimum NPV or the minimum EP. Again, the greatest differences occur with C1, which tends to increase the thickness of the insulating layers for both the optima.

The NSGA-II then shows a good robustness when the solutions are optimized in terms of NPV and EP. In fact, substantial changes are noted on the thermal discomfort of optima solutions. This greater sensitivity of the WDT index to solar irradiation implies a decrease of MOO robustness when the minimization of WDT becomes an objective.

5. Nomenclature

Symbols

A	area (m ²)
COND	Condensing boiler
DH	Double glazing with high SHGC
S	Surface of dispersing envelope (m ²)
SG	Single Glazing
SHGC	Solar heat gain coefficient (-)
STD	Standard boiler
TH	Triple glazing with high SHGC
V	Conditioned volume (m ³)

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