Influence of Solar Irradiance Models on the Selection of Optimal Refurbishment Measures

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Abstract

Building Energy Simulation (*BES*) is the basis for the prediction of energy demand not only for the new buildings design but also for the support of energy retrofit design. However, the different accuracy of implemented models, such as those related to the processing of solar irradiance can lead to uncertainties in determining optimal retrofit solutions. In this work, we analysed the impact of the solar irradiance models in *BES* in the context of multi-objective optimization to guide the refurbishment process, considering economic, energy and thermal comfort goals.

Introduction

In the last decades, International Organizations and Governments have issued directives and regulations to promote high efficiency performance for renovation of the existing building stock. For example, considering the European Union regulatory framework, the latest developments have addressed new requirements for existing buildings and nearly zero energy targets, to be assessed by means of advanced energy performance calculation analysis. In particular, the European Institutions have promoted the calculation of the so called "cost-optimal" requirement, i.e., the search of an energy performance level leading to the lowest cost during the estimated economic lifecycle (European Commission 2010 and 2012). Moreover, energy savings have to be achieved without compromising the proper indoor thermal comfort for the occupants.

In many cases, the set of energy saving measures (*ESMs*) ensuring the cost-optimal can be identified only by means of complex Multi-Objective Optimization (*MOO*) techniques, evaluating a large number of alternatives in order to optimize economic, energy and thermal comfort aspects. This means, for example, minimizing the net present value of the refurbishment investment, the primary energy uses for space heating and cooling and the time in discomfort conditions. As it can be easily figured out, a reliable prediction of the impact of each energy measure on potential savings and changes to indoor thermal conditions is crucial to select the best ones. Moreover, relative accuracy, which is necessary for the comparison, is not enough for *MOO* purposes and an absolute accuracy of the results of cost-optimal measures is required, especially when they are considered for energy policy by the Governments.

It is widely recognized that *MOO* results can be dependent on the specific features of the adopted technique (Wright and Alajmi 2005, Ihm and Krarti 2012), on the characteristics of *BES* models and, in particular, on the used inputs. For this reason, the verification of the robustness of the results is a key aspect in the optimization process. In the literature, some works dealt with the robustness of optimal solutions to the algorithm parameters (Wright and Alajmi 2005, Ihm and Krarti 2012) while other researches (Prada *et al.* 2014, Prada *et al.* 2015b and 2015c) focused on the robustness of the *MOO* Genetic Algorithm, *GA*, to the uncertainty introduced by some *BES* boundary conditions, especially to the weather data. Indeed, a large number of algorithms are available for the estimation of direct and diffuse solar irradiance starting from hourly profiles of horizontal global irradiance collected by many meteorological stations around the world. A variety of mathematical and empirical models can be found in literature for both the calculation of irradiance on tilted surfaces (i.e., *irradiance models for tilted surfaces*) and the subdivision of horizontal global solar irradiance into direct and diffuse components (i.e., *horizontal diffuse irradiance models*). As underlined in previous analysis (e.g., Prada *et al.* 2015a), no pair of models can provide results with the same reliability for different worldwide localities, complete datasets of solar irradiance measurements on tilted surfaces are rarely available for robust assessment of the solar models' accuracy and the choice of those models can affect the definition of *ESMs* in 2-objective optimizations minimizing energy uses and costs (Prada *et al.* 2015b and 2015c).

As a further development of the previous research on the impact of *BES* solar irradiance models in the context of multi-objective optimization of retrofit solutions, this work includes, as third goal, the thermal comfort. From a group of 264 combinations of *irradiance models for tilted surfaces* and *horizontal diffuse irradiance models*, the most different pairs were chosen by means of non-parametric statistical techniques and used to pre-process the hourly solar irradiance profiles for *BES*. The developed profiles were used in different *MOO*, involving 12 reference buildings in two Italian climates. Sensitivity of Pareto's fronts and of the optimal sets of *ESMs* were discussed. The two climates and the buildings included in the study revealed a different sensitivity of the results to the choice of solar models, both regarding the shape of the Pareto's front and the optimal energy saving measures.

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With respect to previous researches performed on only economic and energy goals, with the thermal comfort objective accounted for, the impact of the choice of solar irradiance models on the optimal retrofit solution is increased.

Method

Case study

Coherently with the previous works on this topic (i.e., Prada *et al.* 2015b and 2015c), the analysis was performed on two building typologies defined basing on the most significant variables affecting the building energy balance (Pernigotto *et al.* 2014a). The investigated buildings are a semi-detached house (with a compactness ratio, S/V = 0.97 m^{-1}) and an intermediate flat in a multi-storey building (S/V = 0.3 m^{-1}). The envelope surfaces are directly exposed to the external environment, except in case of adjacency to other heated apartments, for which adiabatic boundary condition is imposed. These buildings were developed starting from a reference module, i.e., a typical flat with 100 m^2 floor surface, 3 m internal height and window to floor ratio equal to 0.144. For sake of simplicity, façades are oriented towards the main cardinal directions and all windows are facing either south or east. Two alternatives of opaque envelope were modelled: the thermal transmittances of *REF1* buildings are representative of the constructions built prior to the first Italian energy law, i.e., law 373/1976 (Italian Parliament 1976), whereas those of *REF2* cases are in compliance with the second energy legislations (Italian Parliament 1991). The infiltration rate was estimated according to EN 12207 (CEN 1999) and EN 15242 (CEN 2007a) with a reference air tightness n_{50} equal to 7 ACH. The associated infiltration rates were 0.20 and 0.062 ACH, respectively for semi-detached houses and intermediate flats. As regard the system, a standard gas boiler was coupled with radiators and on-off control system. As a whole, the combination of all alternatives gave 12 buildings to optimize by means of a *GA*.

Energy Saving Measures

NSGA-II (Deb *et al.* 2002), an Elitist Non-dominated sorting *GA* algorithm, was implemented in Matlab® to find the optimal sets of *ESMs*. The primary energy for space heating EP_h, the net present value *NPV* and the weighted thermal discomfort time *WDT* were minimized in a triple-objective optimization. The fitness function written in Matlab® code launched TRNSYS 17 code, read the *BES* output file and computed the *NPV* by means of the method proposed by Commission delegated regulation (EU) No 244/2012 and the *WDT* according to the Annex F of EN 15251:2007 (CEN 2007b).

Conventional *ESMs* applied to either envelope and *HVAC* components were considered in the analysis. Indeed, the European Commission expects that mature off-the-shelf technologies allow a total energy consumption reduction of one-third (European Commission 2014) because of their lower initial investment with respect to renewable source systems.

The following *ESMs* were taken as eligible in *MOO*:

1. external insulation of the opaque envelope with an EPS additional layer (thermal conductivity of 0.04 W m^{-1} K^{-1}, specific heat of 1470 J kg^{-1} K^{-1} and specific mass of 40 kg m^{-3}) with thicknesses multiple of centimetres and ranging from 0 to 20 cm. The insulation thickness was changed independently for vertical walls, roof and floor as well as different installation costs were considered;
2. replacement of existing single glazing windows *S* with more efficient glazing systems (i.e., double, *D*, or triple, *T*, glazing with aluminium frames and thermal break coupled with either high, *H*, or low, *L*, *SHGC*);
3. replacement of the standard boiler (*STD*) with either a modulating (*MOD*) or condensing boiler adjusted by a climatic control (*COND*);
4. installation of a mechanical ventilation system (*MVS*) with a cross flow heat recovery system.

Further details about the chosen *ESMs* and the initial investments, derived from Italian regional price lists, can be found in (Penna *et al.* 2015).

The adoption of these *ESMs* introduced some subsequent improvements, which were accounted for in energy calculations:

1. reduction of the linear transmittances of the thermal bridges because of envelope insulation and windows replacement, modelled by means of a polynomial regression derived by Penna *et al.* (2015);
2. halving of air leakages and infiltration rates with new glazing systems;
3. reduction of distribution losses because of lower inlet water temperature of the radiators.

Selection of representative solar irradiance models

The analysis was performed for the climates of two Italian cities: Monza (latitude: 45.57° N; longitude 9.35° E; altitude: 162 m) with a mixed-humid climate in class 4A (ASHRAE 2013) and Rome (latitude: 41.78° N; longitude 12.13° E; altitude: 3 m) with a warm marine in class 3C (ASHRAE 2013). IWEC weather data (WMO station 162420 at Roma-Fiumicino Airport) provided the global solar irradiance profile for Rome while a reference weather file was developed starting from multi-year hourly series from Monza meteorological stations (Pernigotto *et al.* 2014b).

In previous parts of this research (Prada *et al.* 2015a), 22 *horizontal diffuse irradiance models* and 12 *irradiance models for tilted surfaces* were analysed and all 264 factorial combinations were implemented to calculate the hourly distributions of solar irradiance for the vertical surfaces oriented towards the four cardinal points in both cities. In this work, three reference pairs of models were identified in each climate by means of a procedure based on non-parametric tests similar to the approach for the development of reference years (Pernigotto *et al.* 2014b) and specifically defined to perform a robust selection of different combinations. First, for each orientation and hour between dawn and dusk time, the median of the 264 values was found and the median profile developed. Then, each profile of solar irradiance values was tested against the median profile for its orientation by means of Kolmogorov-Smirnov statistics. For each orientation, pairs of models were ranked according to their similarity to the median profiles (i.e., value of Kolmogorov-Smirnov statistics and statistical significance with respect to a significance level of 5 %). Summing up the ranking positions for the cardinal orientation, a global ranking was developed for each climate. Thanks to this approach, we selected the pair of models closest to the median profile and the top-20 of the most different ones, which were later mutual tested in order to find two pairs statistically different, one underestimating and one overestimating with respect to pair closest to the median profile.

All the pairs of selected models are summarized in Table 1. "Models 1" are those underestimating the available solar irradiance, "Models 2" are those closest to the median and "Models 3" are those with the tendency to overestimate the irradiance. As it can be noticed, the *irradiance models for tilted surfaces* are the same for both localities, which differentiate from each other for the *horizontal diffuse irradiance models*.

Table 1 – Selected pairs of irradiance models.

		Irradiance model for tilted surface	**Horizontal diffuse irradiance model**
Monza	Models 1	Temps and Coulson (1977)	Perez *et al.* (1992)
	Models 2	Skartveit and Olseth (1986)	Reindl *et al.* (1990)
	Models 3	Klucher (1979)	Chendo and Maduekwe (1994)
Rome	Models 1	Temps and Coulson (1977)	Maxwell (1987)
	Models 2	Skartveit and Olseth (1986)	Orgill and Hollands (1977)
	Models 3	Klucher (1979)	Lam and Li (1996)

Solar *irradiance models for tilted surfaces* can be grouped into three generations (Muneer 2007) and all selected models belong to the second one, which differentiates the radiance distributions between clear and overcast skies. Regarding the *horizontal diffuse irradiance models*, the chosen models propose different kinds of correlations involving the clearness index, i.e., the portion of horizontal extra-terrestrial irradiance reaching the surface, as in Orgill and Hollands (1977), in Lam and Li (1996) and in the first model by Chendo and Maduekwe (1994). The second model by Reindl *et al.* (1990) correlates the diffuse irradiance also with the sine of the solar altitude. Furthermore, the second model by Perez *et al.* (1992) accounts also the dynamic effect in time series by means of a modification to the DISC model introduced by Maxwell (1987).

The *MOO* procedure was run for each pair of selected solar irradiance models, for each building configuration. Pareto's fronts were compared, as well as the solutions in the fronts optimizing one given objective (i.e., the energy performance, the economic and the thermal comfort optima).

Results and discussion

Pareto's fronts

Figure 1 reports an example of the Pareto's front, which is a 3-dimensional surface. In order to simplify the description of these fronts, they have been projected on three planes: "plane 1" depicts *NPV* against EP_h, "plane 2" *WDT* depicts against EP_h and "plane 3" depicts *WDT* against *NPV*. Differently from the charts represented in previous researches (e.g., Prada *et al.* 2015c), the points showed in the three planes cannot be considered 2-dimensional Pareto's fronts since solutions which seem dominated by others in a 2D representation are indeed in the same front when the third dimension is accounted for. When separate groups are detectable, they often depend on the choice of installing a *MVS*: when recommended, lower EP_h, higher *NPV* and lower *WDT* are found.

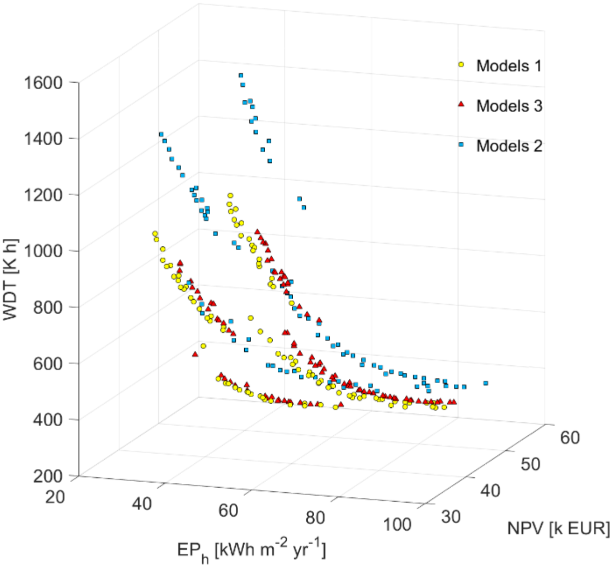

Figure 1 – Pareto's fronts obtained with the different pairs of solar irradiance models for REF1 semi-detached house with east-oriented windows in Monza.

Considering "plane 1" (e.g., Figure 2), the choice of solar irradiance models has small impact on the projected fronts and for the three pairs the profiles are almost overlapped for all *REF1* buildings, especially in Monza. In Rome, this is still true but fronts are more irregular. Analysing the other two planes (e.g., Figures 3 and 4), we can see larger sensitivity of the *WDT* to the solar modelling and, for Rome, more scattered data. As it can be observed, "Models 3" include, in the fronts, solutions with a larger *WDT* estimation. Regarding the different buildings, the *S/V* ratio has a larger impact with respect to the windows' orientation and more compact building shapes emphasize the effect of the solar irradiance models on *WDT*.

For *REF2* buildings, trends are similar. As regard the projections on "plane 1", a slightly larger impact of the solar irradiance pairs can be detected in both climates, especially for buildings with *S/V* = 0.3 m^{-1}. In the other planes the effect of irradiance modelling is dampened when compactness ratios are larger and windows are south-oriented.

Energy performance optima

Analysing the solutions giving the best Energy Performance for space heating among those belonging to the Pareto's surface for *REF1* buildings (Tables 2 and 3), the average of the energy optima is around or less than 0.5 kWh m^{-2} yr^{-1} for all cases with *S/V* = 0.3 m^{-1} in both climates. As regard *S/V* = 0.97 m^{-1}, in Monza the averages are around 25 and 15 kWh m^{-2} yr^{-1}, respectively when windows are east or south-oriented, while in Rome they are 5.5 and 1 kWh m^{-2} yr^{-1}. Dependence of the energy optima on solar modelling is lower for cases with south-oriented windows and, even if for Rome the percentage spread between maximum and minimum values can be large in case of high *S/V*, the absolute deviation is low. For the cases with best *EP$_h$*, the spread of the *NPV* is generally small, while a spread up to almost 50 % and 35 % can be seen regarding the *WDT*, respectively for Monza and Rome. This means that, even if from *EP$_h$* and *NPV* perspective the solutions are similar, the achievable comfort conditions can be significantly different. For example, considering case with *S/V* = 0.3 m^{-1} and east-oriented windows in Monza, while "Models 1" estimate a 2384 K h *WDT*, according to "Models 3" they are 3225 K h. As regard the *ESMs*, a small variability affects insulation thickness, with the largest discrepancy found in Monza comparing recommendations from "Models 1" and "Models 2". In this climate, the most common glazing is always *TH* for all cases except the intermediate flat with south-oriented windows, for which *TL* is proposed if models 2 and 3 are adopted. In Rome, the solutions are similar but in this case *TL* is preferred for the intermediate flat with east-oriented windows. Boiler selection is particularly influenced by the solar irradiance models in Monza and less in Rome. For all building configurations except the intermediate flat with south-oriented windows, whatever the solar irradiance models, all best *ESMs* recommend the *MVS* installation.

The energy optima achievable for *REF2* buildings (Tables 4 and 5) are generally poorer than those of *REF1*: for example, the average energy performance of semi-detached houses is between 32 and 35 kWh m^{-2} yr^{-1} in Monza while this range in Rome is larger than 6 kWh m^{-2} yr^{-1}. In Monza, best *EP$_h$* of cases with east-oriented windows is very sensitive: for example, with *S/V* = 0.3 m^{-1} it ranges from 27 to 41 kWh m^{-2} yr^{-1}. The choice of solar irradiance models significantly affects insulation thickness only for cases with east-oriented windows. While in Monza the proposed glazing is always *TH*, some solar irradiance models recommend no window substitution in Rome. A condensing boiler is generally recommended, exception made for the intermediate flat with south-oriented windows, for which, all models discourage the substitution. *MVS* installation is always indicated, except for case *S/V* = 0.3 m^{-1} with south-oriented windows in Rome: only "Models 2" recommend its adoption, halving *WDT* and doubling *NPV* with negligible impact on *EP$_h$* if compared to the *ESMs* proposed by alternative solar modelling.

Economic optima

The averages of *NPV* optima of *REF1* buildings (Tables 2 and 3) are in the ranges 15 000 - 17 000 € and 33 000 - 37 000 € for Monza and in the ranges 11 000 - 13 000 € and 23 000 - 28 000 € for Rome, respectively for *S/V* = 0.3 m^{-1} and *S/V* = 0.97 m^{-1}. *NPV* deviation is very low, suggesting a limited impact on the solar irradiance models. On the contrary, a large spread is found for the *WDT* of those optima - up to almost 50 % in Monza for *S/V* = 0.97 m^{-1} and 75 % in Rome for *S/V* = 0.30 m^{-1}, in both cases with south-oriented windows. In this latter case, particularly, *WDT* ranges from 2033 to 3526 K h, depending on the solar irradiance models. *EP$_h$* spread is generally within or slightly larger than 20 %, except for the above-mentioned case in Rome, where it ranges from 1.96 to 19.44 kWh m^{-2} yr^{-1} since with "Models 3" only opaque component insulation is proposed in the *NPV* optima, without any window substitution, bringing an equivalent *NPV* but a very different *EP$_h$*. Besides this noticeable case, *ESMs* solutions are most alike, independently of the solar irradiance models, whose impact is limited to 1 or 2 cm in the insulation of the opaque elements. Starting windows are recommended to be substituted with *DH* but changes to the boiler, as well as the *MVS* installation, are never recommended.

For *REF2* buildings (Tables 4 and 5), averages of *NPV* optima are similar to those of *REF1* cases. *NPV* spread is still very low and findings about variability discussed for *REF1* cases can be confirmed, excluding *EP$_h$* in the following two configurations in Monza. For intermediate flat with south-oriented windows, "Models 1" propose the installation of new *DH* glazings, passing from an *EP$_h$* around 37 kWh m^{-2} yr^{-1} of the other solar models to almost 16 kWh m^{-2} yr^{-1}. Similarly, for semi-detached house with east-oriented windows, "Models 2" propose insulation of about 18 cm while 10 or 11 cm is the most common choice for other models. Regarding the choice of *ESMs*, except for the mentioned cases, impact of solar models is often negligible: in Monza *DH* glazing is often selected, except the already mentioned intermediate flat with south-oriented windows, but no boiler substitution or *MVS* are proposed. In Rome, there is no different intervention involving windows or system components for *REF2* buildings.

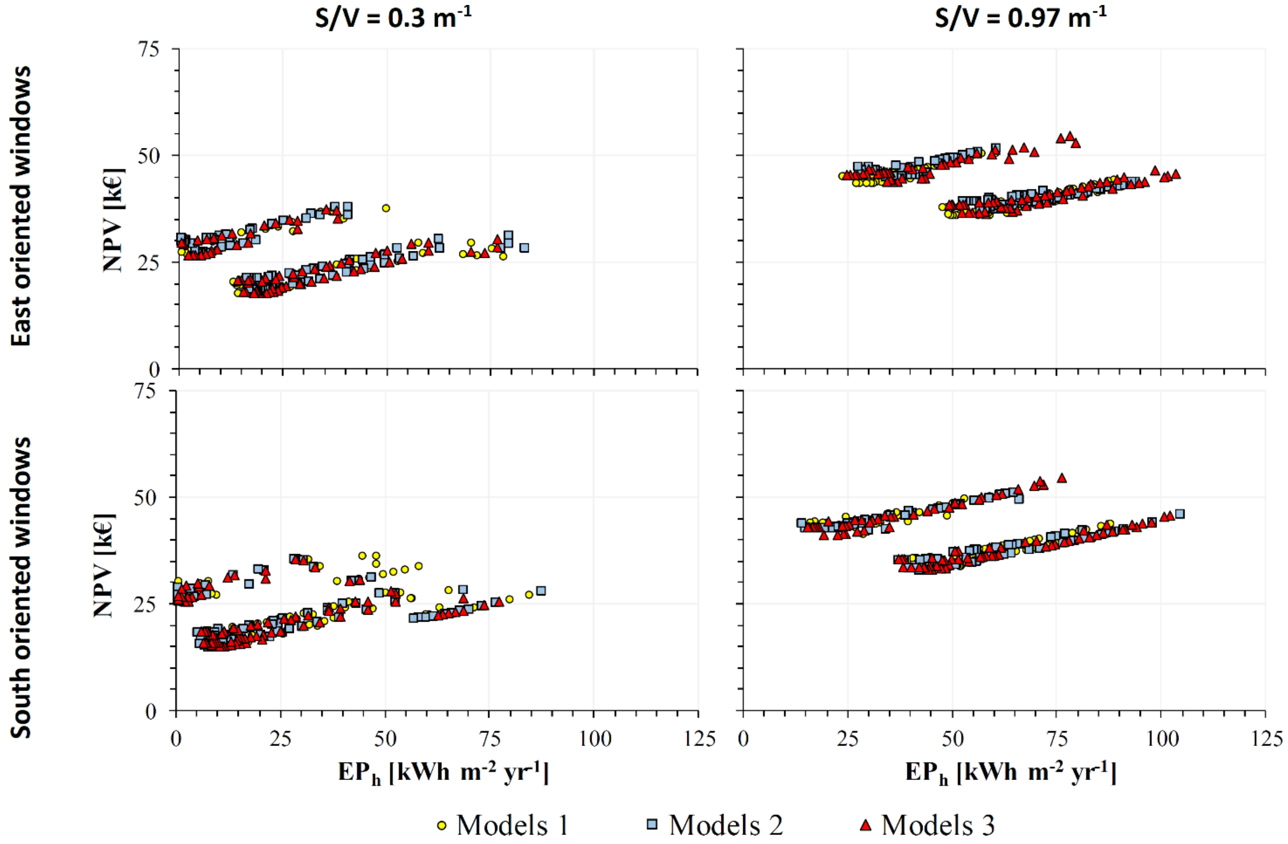

Figure 2 – Projection on "plane 1" (NPV and EP_h) of Pareto's fronts obtained for REF1 buildings in Monza.

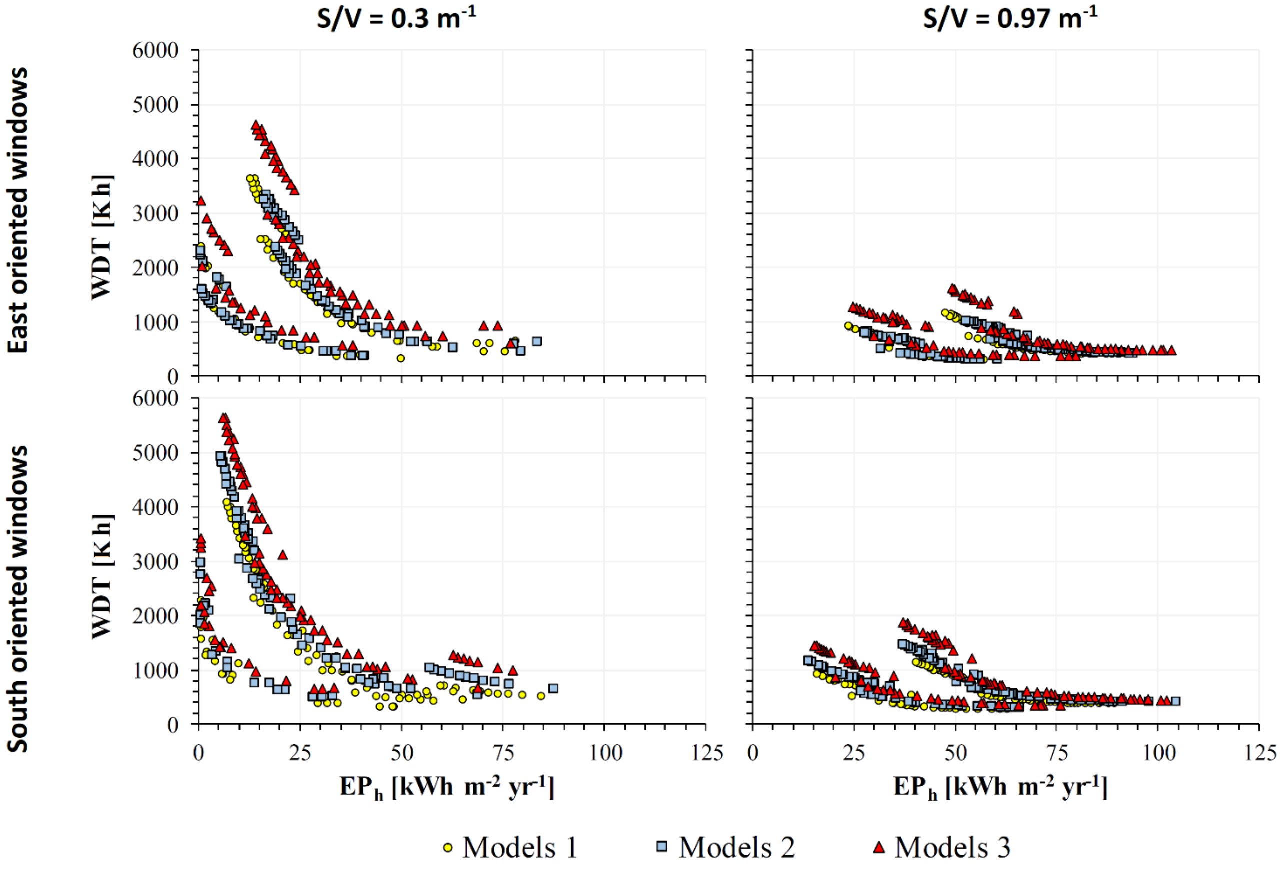

Figure 3 – Projection on "plane 2" (WDT and EP_h) of Pareto's fronts obtained for REF1 buildings in Monza.

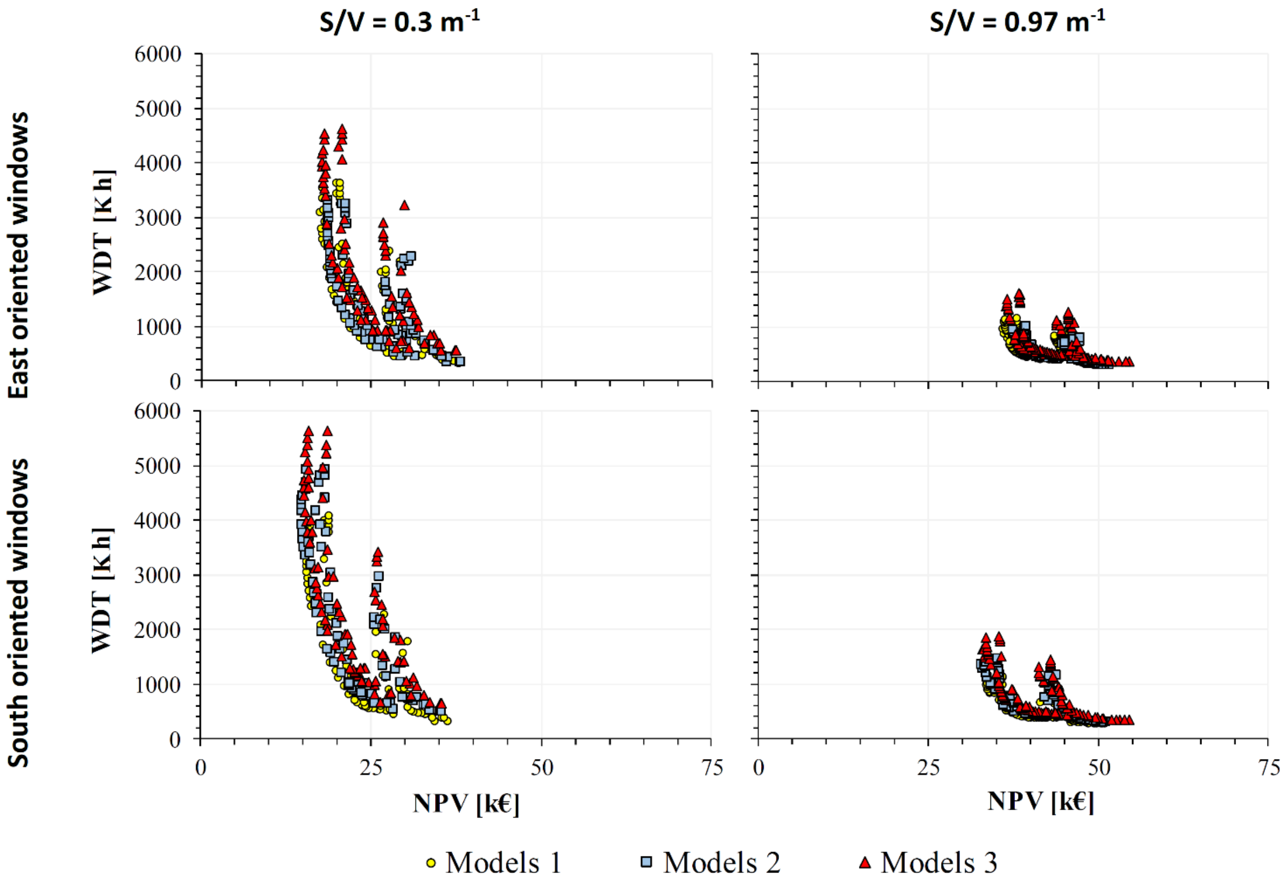

Figure 4 – Projection on "plane 3" (WDT and NPV) of Pareto's fronts obtained for REF1 buildings in Monza.

Table 2 – Optima for REF1 buildings in Monza.

		East windows orientation			South windows orientation			East windows orientation			South windows orientation		
		Intermediate flat in multi-story buildings S/V=0.30 m^{-1}						Semi-detached houses S/V=0.97 m^{-1}					
		Models 1	Models 2	Models 3	Models 1	Models 2	Models 3	Models 1	Models 2	Models 3	Models 1	Models 2	Models 3
REF1 - EPh optima													
Insulation thickness [cm]	**Wall**	17	20	19	13	17	15	19	18	19	19	18	19
	Roof	0	0	0	0	0	0	17	20	18	18	19	19
	Floor	0	0	0	0	0	0	19	17	18	19	19	17
Window		TH	TH	TH	TH	TL	TL	TH	TH	TH	TH	TH	TH
Boiler		STD	COND	MOD	STD	STD	STD	MOD	COND	MOD	COND	COND	MOD
Ventilation		MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP_h [kWh m^{-2} yr^{-1}]		0.5	0.5	0.5	0.5	0.5	0.5	23.6	27.5	24.8	15.9	14.0	15.4
NPV [k€]		27.4	30.7	29.7	26.9	27.1	26.8	45.2	47.3	45.6	44.2	43.8	43.0
WDT [K h]		2384	2296	3225	2285	2002	2204	923	801	1276	918	1171	1445
REF1 - NPV optima													
Insulation thickness [cm]	**Wall**	18	18	17	17	17	15	16	16	17	17	17	17
	Roof	0	0	0	0	0	0	16	17	15	16	17	16
	Floor	0	0	0	0	0	0	15	16	15	16	17	15
Window		DH	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH
Boiler		STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Ventilation		NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT
EP_h [kWh m^{-2} yr^{-1}]		17.3	21.4	19.0	10.9	8.5	10.5	56.2	60.0	58.1	46.1	42.0	45.1
NPV [k€]		17.4	18.5	17.7	15.5	14.9	15.1	35.9	37.4	36.4	33.5	32.8	33.0
WDT [K h]		3110	2854	4037	3350	4274	4732	960	905	1378	999	1359	1626
REF1 - WDT optima													
Insulation thickness [cm]	**Wall**	0	1	1	0	1	1	9	8	8	8	7	11
	Roof	0	0	0	0	0	0	18	18	16	18	17	18
	Floor	0	0	0	0	0	0	4	5	2	3	3	1
Window		DL	TL	TL	DL	TL	TL	TL	TL	TL	TL	TL	TL
Boiler		COND	STD	MOD	STD	MOD	COND	MOD	COND	STD	MOD	STD	MOD
Ventilation		MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP_h [kWh m^{-2} yr^{-1}]		49.9	40.8	38.0	48.0	30.6	28.5	60.3	60.6	79.7	62.8	66.1	76.1
NPV [k€]		37.7	35.9	37.2	34.3	35.1	35.5	50.7	51.7	53.0	51.0	49.5	54.6
WDT [K h]		331	360	558	327	496	643	300	300	361	276	309	346

Table 3 – Optima for REF1 buildings in Rome.

		East windows orientation			**South windows orientation**			**East windows orientation**			**South windows orientation**		
		Intermediate flat in multi-story buildings S/V=0.30 m^{-1}						**Semi-detached houses S/V=0.97 m^{-1}**					
		Models 1	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**
REF1 - EPh optima													
Insulation thickness [cm]	**Wall**	19	19	19	13	16	12	18	18	19	19	19	19
	Roof	0	0	0	0	0	0	18	19	19	18	19	20
	Floor	0	0	0	0	0	0	19	19	20	19	20	19
Window		TL	TL	TL	TH	TH	TH	TH	TH	TH	TH	TH	TH
Boiler		COND	STD	STD	COND	COND	COND	COND	COND	COND	MOD	COND	COND
Ventilation		MVS	MVS	MVS	NAT	NAT	NAT	MVS	MVS	MVS	MVS	MVS	MVS
EP$_h$ [kWh m^{-2} yr^{-1}]		0.4	0.4	0.4	0.3	0.3	0.3	5.2	6.5	4.9	1.2	1.3	0.8
NPV [k€]		30.2	27.3	27.3	16.1	16.5	16.0	41.2	41.7	41.6	39.4	40.7	40.6
WDT [K h]		2822	2851	3434	5488	7160	7277	1886	1912	2477	1661	2023	2313
REF1 - NPV optima													
Insulation thickness [cm]	**Wall**	11	13	11	7	7	15	14	14	15	14	14	14
	Roof	0	0	0	0	0	0	13	12	12	13	11	12
	Floor	0	0	0	0	0	0	13	13	12	12	12	12
Window		DH	DH	DH	DH	DH	S	DH	DH	DH	DH	DH	DH
Boiler		STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Ventilation		NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT
EP$_h$ [kWh m^{-2} yr^{-1}]		4.8	5.6	5.0	2.0	2.2	19.4	27.8	31.5	29.0	19.6	20.5	16.9
NPV [k€]		13.1	13.5	13.1	11.8	11.8	11.2	26.9	27.7	26.9	24.5	24.3	23.5
WDT [K h]		4669	5070	5989	3526	4364	2033	1786	1789	2260	1478	1743	2058
REF1 - WDT optima													
Insulation thickness [cm]	**Wall**	0	1	0	1	0	0	1	1	1	1	1	1
	Roof	0	0	0	0	0	0	17	16	16	16	16	16
	Floor	0	0	0	0	0	0	2	3	3	3	3	2
Window		TL	S	DL	S	S	S	TL	TL	TL	TL	TL	TL
Boiler		MOD	MOD	STD	MOD	STD	STD	COND	COND	COND	COND	COND	MOD
Ventilation		MVS	MVS	MVS	MVS	NAT	NAT	MVS	MVS	MVS	MVS	MVS	MVS
EP$_h$ [kWh m^{-2} yr^{-1}]		24.6	51.9	26.5	35.0	59.8	54.8	59.3	57.4	55.6	49.7	49.9	54.7
NPV [k€]		30.2	33.7	28.5	29.1	17.0	15.6	49.6	49.1	48.6	47.0	47.0	47.2
WDT [K h]		453	572	684	422	599	761	255	262	319	222	237	256

Table 4 – Optima for REF2 buildings in Monza.

		East windows orientation			**South windows orientation**			**East windows orientation**			**South windows orientation**		
		Intermediate flat in multi-story buildings S/V=0.30 m^{-1}						**Semi-detached houses S/V=0.97 m^{-1}**					
		Models 1	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**
REF2 - EPh optima													
Insulation thickness [cm]	**Wall**	12	20	12	12	11	12	12	19	12	11	11	11
	Roof	0	0	0	0	0	0	12	19	11	11	11	12
	Floor	0	0	0	0	0	0	12	20	12	12	12	11
Window		TH	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH
Boiler		COND	STD	COND	STD	STD	STD	COND	COND	COND	COND	COND	COND
Ventilation		MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP$_h$ [kWh m^{-2} yr^{-1}]		1.5	0.7	2.2	0.5	0.5	0.5	38.5	27.2	41.5	33.4	31.7	32.2
NPV [k€]		29.9	27.9	30.1	29.7	29.5	29.7	46.8	47.7	47.4	45.1	44.6	44.7
WDT [K h]		2026	2229	2699	2168	2664	3249	643	832	898	605	763	969
REF2 - NPV optima													
Insulation thickness [cm]	**Wall**	12	18	12	11	11	11	10	18	10	10	10	10
	Roof	0	0	0	0	0	0	11	17	11	11	11	11
	Floor	0	0	0	0	0	0	11	18	11	11	11	11
Window		DH	DH	DH	DH	S	S	DH	DH	DH	DH	DH	DH
Boiler		STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Ventilation		NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT
EP$_h$ [kWh m^{-2} yr^{-1}]		22.8	22.7	24.0	15.9	36.2	37.1	71.9	58.7	73.9	63.3	61.1	61.7
NPV [k€]		18.1	18.9	18.4	16.1	15.2	15.5	37.6	37.7	38.1	35.2	34.6	34.8
WDT [K h]		2567	2796	3477	2665	1635	2120	720	950	1019	698	894	1153
REF2 - WDT optima													
Insulation thickness [cm]	**Wall**	0	1	0	1	0	0	12	9	5	9	7	5
	Roof	0	0	0	0	0	0	12	18	11	11	11	11
	Floor	0	0	0	0	0	0	3	5	3	3	3	3
Window		TL	TL	TL	TL	TL	TL	TL	TL	TL	TL	TL	TL
Boiler		MOD	MOD	MOD	STD	STD	STD	MOD	MOD	MOD	STD	MOD	MOD
Ventilation		MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP$_h$ [kWh m^{-2} yr^{-1}]		51.5	41.1	53.0	31.8	45.1	45.1	70.5	62.9	84.1	70.1	71.9	76.9
NPV [k€]		37.5	38.0	37.9	35.5	35.7	35.8	52.4	51.6	54.9	49.7	51.9	53.0
WDT [K h]		313	357	450	388	389	511	320	304	385	304	331	380

Table 5 – Optima for REF2 buildings in Rome.

		East windows orientation			South windows orientation			East windows orientation			South windows orientation		
		Intermediate flat in multi-story buildings S/V=0.30 m^{-1}						Semi-detached houses S/V=0.97 m^{-1}					
		Models 1	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**	**Models 1**	**Models 2**	**Models 3**
REF2 - EPh optima													
Insulation thickness [cm]	**Wall**	8	13	12	12	7	12	19	18	18	11	11	11
	Roof	0	0	0	0	0	0	19	19	17	11	11	11
	Floor	0	0	0	0	0	0	20	19	18	12	12	11
Window		TH	DH	DH	TH	DH	TH	TH	TH	DH	TH	TH	TH
Boiler		COND	COND	COND	STD	STD	STD	COND	COND	COND	COND	COND	COND
Ventilation		MVS	MVS	MVS	NAT	MVS	NAT	MVS	MVS	MVS	MVS	MVS	MVS
EP$_h$ [kWh m^{-2} yr^{-1}]		0.4	0.4	0.4	0.4	0.4	0.3	5.0	7.0	7.9	7.5	7.7	6.3
NPV [k€]		29.1	28.6	28.5	13.1	27.8	13.1	41.7	41.9	40.4	38.0	38.0	37.5
WDT [K h]		3138	3620	4476	5140	3209	7150	1905	1868	2266	1108	1317	1482
REF2 - NPV optima													
Insulation thickness [cm]	**Wall**	15	16	14	11	11	11	15	15	14	9	9	10
	Roof	0	0	0	0	0	0	12	12	12	10	10	11
	Floor	0	0	0	0	0	0	12	13	13	11	11	10
Window		S	S	S	S	S	S	S	S	S	S	S	S
Boiler		STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Ventilation		NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT
EP$_h$ [kWh m^{-2} yr^{-1}]		17.7	20.4	18.3	9.2	9.2	6.2	49.7	52.8	49.7	45.7	45.0	40.5
NPV [k€]		10.7	11.6	10.7	7.9	7.8	7.0	26.2	27.2	26.3	23.7	23.5	22.4
WDT [K h]		2596	2717	3490	2038	2620	3181	1021	1060	1428	679	871	1059
REF2 - WDT optima													
Insulation thickness [cm]	**Wall**	0	0	0	0	0	0	1	1	1	2	1	2
	Roof	0	0	0	0	0	0	16	17	16	11	11	11
	Floor	0	0	0	0	0	0	2	3	3	3	3	1
Window		DL	DL	DL	TL	TL	TL	TL	TL	TL	TL	TL	TL
Boiler		STD	STD	MOD	STD	STD	STD	MOD	MOD	COND	COND	COND	COND
Ventilation		NAT	NAT	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
EP$_h$ [kWh m^{-2} yr^{-1}]		42.8	45.4	25.8	16.9	18.6	16.2	64.4	61.5	55.5	46.6	52.3	55.6
NPV [k€]		19.3	20.0	30.2	29.0	28.5	27.9	49.9	49.5	48.6	45.2	46.6	47.3
WDT [K h]		601	622	698	384	483	610	252	256	316	238	248	266

Thermal comfort optima

The largest impact of solar irradiance models is found for *WDT* optima. In Monza, averages of *REF1* cases (Tables 2 and 3) are between 410 and 480 K h for the intermediate flats and between 310 and 330 K h for the semi-detached houses, respectively for east and south-oriented windows. In Rome, discomfort conditions of *WDT* optima are larger for intermediate flats (i.e., averages in the range 570 – 600 K h) but smaller for semi-detached houses (i.e., averages in the range 230 – 280 K h). Spread is particularly high (i.e., from 50 to 65 % in Monza and from 40 to 60 % in Rome) for intermediate flats while it is around 20 % for semi-detached houses. For example, a building located in Monza with *S/V* equal to 0.3 m^{-1} and south-exposed windows can have a *WDT* ranging from 327 to 643 K h, depending on the models adopted in solar irradiance calculation. Again, the *NPV* of *WDT* optima demonstrate a general poor sensitivity, except for the intermediate flats in Rome.

ESMs for buildings with *S/V* = 0.3 m^{-1} include limited (i.e., 1 cm) or null insulation and *TL* glazing is the most common choice. However, in Monza “Models 1” indicate *DL* as the proper choice in case on *S/V* = 0.3 m^{-1}. If east-oriented, in Rome those buildings have more contrasting recommendations by using different solar models, including also the option of no window substitution. For all buildings and models, solar irradiance models give different indications about the boiler to choose and, only for *S/V* = 0.3 m^{-1} and south-oriented windows in Rome, if installing *MVS* or not.

Regarding the *REF2* cases (Tables 4 and 5), ranges of *WDT* optima are similar as for *REF1* cases and their spread is remarkably lower. A similar consideration can be drawn for the corresponding *EP$_h$* deviations. *ESMs* are similar to those of *REF1* cases but, this time, there is much less influence of the choice of solar irradiance models. In Monza, *TL* glazing and *MVS* are always selected and modulating boiler is often proposed, except for the intermediate flat with south-oriented windows, for which there is no boiler change at all. Rome has similar sets of measures about windows and mechanical ventilation, except for the intermediate flat with east-oriented windows, for which *DL* is recommended and only with “Models 3” *MVS* is proposed. As regard the boiler, in case of south-oriented windows no substitution is proposed with *S/V* = 0.3 m^{-1} and a condensing boiler is the best choice if *S/V* is 0.97 m^{-1}. As a whole, if windows are east-oriented, the choice of boiler is more influenced by solar modelling in Rome climates.

Conclusion

In this work, the robustness of energy saving measures determined by means of multi-objective optimization was assessed with respect to the choice of solar irradiance models in building energy simulation codes. The genetic algorithm *NSGA-II* was adopted as *MOO* technique and three different quantities were minimized: the primary energy uses for space heating, the net present value of the refurbishment investment and the weighted discomfort time. The analysis was performed with TRNSYS for 12 reference buildings in two Italian climates, Monza and

Rome. Among 264 pairs of *solar irradiance models for tilted surfaces* and *horizontal diffuse irradiance models*, for each city, 3 couples were chosen through non-parametric Kolmogorov-Smirnov test, selecting a couple closest to the median profile of the sample, one remarkably underestimating the solar irradiance availability and one overestimating.

Different solar irradiance models affect the shape of Pareto's front. While the choice of models has a small impact on primary energy uses and net present values, especially for the climate with largest heating demand and for the most inefficient buildings, a large sensitivity is seen regarding the weighted discomfort time. Considering the interaction with the buildings' characteristics, compactness ratio has a larger influence on the shape of the Pareto's front with respect to the windows' orientation and more compact buildings emphasize the role of the solar modelling.

The analysis of the single-objective optima confirmed the higher sensitivity of the weighted discomfort time to the estimation of solar irradiance. Considering the energy performance optima, in each climate, even if the sets estimated with the three pairs of models have similar primary energy consumption and net present values, the achievable comfort conditions can be very different. For the most inefficient existing buildings, the boiler selection is particularly influenced by how the solar irradiance is modelled while for the most recent existing building, less energy inefficient, in some cases the recommended insulation thicknesses resulted very affected. The economic optima are the less affected by the adopted solar irradiance models, both considering the predicted net present values and the proposed energy saving measures for most of cases. Finally, thermal comfort optima registered the largest impacts and discrepancies in the minimum weighted discomfort time can reach even more than 50 %. In some building configurations belonging to the most inefficient ones, the selected energy saving measures are contrasting: for example, in Rome often there is disagreement about the glazing to choose and the boiler to install. However, for most recent buildings, influence of solar modelling on comfort optima is lower.

As a whole, including comfort in multi-objective optimizations, besides energy and economic goals, we observed that the optimal energy saving measures determined by means of a 3-objective optimization are much more influenced by the choice of solar irradiance models than those from a 2-objective one. Economic optima are the most robust while thermal comfort optima are the least ones. While *NSGA-II* demonstrated a good robustness if only energy and economic goals are accounted, when thermal comfort has to be optimized, the choice of solar models cannot be overlooked and a preliminary analysis to assess which models are the most representative for a given locality should be performed.

Nomenclature

BES	Building Energy Simulation
COND	Condensing Boiler
DH	Double Glazing with High *SHGC*
DL	Double Glazing with Low *SHGC*
EP_h	Primary Energy for Space Heating [kWh m^{-2} yr^{-1}]
ESM	Energy Saving Measure
GA	Genetic Algorithm
MOD	Modulating Boiler
MOO	Multi-Objective Optimization
MVS	Mechanical Ventilation System
NPV	Net Present Value [EUR]
S	Single Glazing
STD	Standard Boiler
SHGC	Solar Heat Gain Coefficient [-]
S/V	Building Compactness Ratio [m^{-1}]
TH	Triple Glazing with High SHGC
TL	Triple Glazing with Low SHGC
WDT	Weighted Discomfort Time [K h]

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References

ASHRAE. 2013. *ANSI/ASHRAE/IESNA Standard 90.1, Energy standard for buildings except low-rise residential buildings*. Atlanta, U.S..

CEN European Committee for Standardization. 1999. *EN 12207, Windows and doors. Air permeability – classification*. Brussels, Belgium.

CEN European Committee for Standardization. 2007a. *EN 15242, Ventilation for buildings – calculation method for the determination of air flow rates in buildings including infiltration*. Brussels, Belgium.

CEN European Committee for Standardization. 2007b. *EN 15251, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Brussels, Belgium.

Chendo, M.A.C., Maduekwe, A.L. 1994. Hourly global and diffuse radiation of Lagos, Nigeria - correlation with some atmospheric parameters. *Solar Energy* 52(3):247–251.

Deb, K., Pratap, A., Agarwal, S. 2002. A Fast and Elitist Multi-objectives Genetic Algorithm: NSGA-II. *IEE Transactions on Evolutionary Computation* 6(2):182-197.

European Commission. 2010. Directive 2010/31/EU of the European Parliament and of the council of 19th May 2010 on the energy performance of buildings (recast). *Official Journal of European Union* 153: 13 – 35.

European Commission. 2012. Commission delegated regulation (EU) No 244/2012 of 16th January 2012. *Official Journal of European Union* L81/18.

European Commission, , DG Energy 2014. *Technical Guidance, Financing the energy renovation of buildings with cohesion policy funding*. Brussels, Belgium.

Klucher, T.M. 1979. Evaluation of models to predict insolation on tilted surfaces. *Solar Energy* 23(2): 111–114.

Ihm, P., Krarti, M. 2012. Design optimization of energy efficient residential buildings in Tunisia. *Building and Environment* 58: 81-90.

Italian Parliament. 1976. Law 373 Norme per il contenimento del consume energatico per usi termici negli edifici. *Gazzetta Ufficiale - Serie generale* 148.

Italian Parliament. 1991. Law 10, Norme per l’attuazione del piano energetico nazionale in materia di uso nazionale dell’energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia. *Gazzetta Ufficiale* 13 - *Suppl. Ordinario* 6.

Lam, J.C., Li, D.H.W. 1996. Correlation between global solar radiation and its direct and diffuse components. *Building and Environment* 31(6):527–535.

Maxwell, E.L. 1987. A quasi-physical model for converting hourly global horizontal to direct normal insolation. *Technical Report of Solar Energy Research Institute, SERI/TR-215-3087*.

Muneer, T. 2007. *Solar radiation and daylight models*. Oxford, U.K.: Butterworth-Heinemann.

Orgill, J.F., Hollands, K.G.T. 1977. Correlation equation for hourly diffuse radiation on a horizontal surface. *Solar Energy* 19(4): 357 – 359.

Penna, P., Prada, A., Cappelletti, F., Gasparella, A. 2015. Multi-objectives optimization of Energy Efficiency Measures in existing buildings. *Energy and Buildings* 95:57–69.

Perez, R.R., Ineichen, P., Maxwell, E.L. 1992. Dynamic global-to-direct irradiance conversion models. *ASHRAE Transactions* 98(1): 354-369.

Pernigotto, G., Prada, A., Gasparella, A., Hensen, J.L.M. 2014a. Development of sets of simplified building models for building simulation. *Proc. of 3rd International High Performance Building Conference at Purdue*, West Lafayette, Indiana, U.S..

Pernigotto, G., Prada, A., Gasparella, A., Hensen, J.L.M. 2014b. Analysis and Improvement of the Representativeness of EN ISO 15927-4 Reference Years for Building Energy Simulation. *Journal of Building Performance Simulation* 7(6): 391-410.

Prada, A., Pernigotto, G., Cappelletti, F., Gasparella, A., Hensen, J.L.M. 2014. Robustness of multi-objective optimization of building refurbishment to suboptimal weather data. *Proc. of 3rd International High Performance Building Conference at Purdue, West Lafayette*, Indiana, U.S..

Prada, A., Pernigotto, G., Gasparella, A. Mahdavi, A. 2015a. Combined effects of diffuse fraction and tilted surface radiation models. *Proc. Of ECPPM 2014 - 10th European Conference on Product & Process Modelling*, Vienna, Austria.

Prada, A., Pernigotto, G., Cappelletti, F., Gasparella, A. 2015b. Robustness of multi-objective optimization of building refurbishment to solar radiation model. *Proc. Of BSA 2015* – 2nd IBPSA-Italy Conference, Bolzano, Italy.

Prada, A., Pernigotto, G., Cappelletti, F., Gasparella, A. 2015c. Impact of solar irradiation models on building refurbishment measures from multi-objective optimization. *Proc. Of 14th Building Simulation*, p. 2809-2816.

Reindl, D., Beckman, A., Duffie, J.A. 1990. Diffuse fraction correlations. *Solar Energy* 45(1):1–7.

Skartveit, A., Olseth, J.A. 1986. Modelling slope irradiance at high latitudes. *Solar Energy* 36(4):333–344.

Temp, R.C., Coulson, K. L. 1977. Solar radiation incident upon slopes of different orientations. *Solar Energy* 19(2):179–184.

Wright, J., Alajmi, A. 2005. The robustness of genetic algorithms in solving unconstrained building optimization problems. *Proc. of 9th Building Simulation*, p. 1361-1368.