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The effect of weather datasets on building energy simulation outputs

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Abstract

Results of dynamic energy simulations of buildings are affected by many uncertainties, which are the main reason of the performance gap registered between simulated and operational performance. They depend mostly on the incorrect modelling of building components and their properties, the inadequate characterization of operational schedules, the limitations in the simulation algorithms used by energy simulation software, the quality and reliability of data contained in weather files. The first three limiting factors are somehow under the control and capacity of the person in charge of the simulation, that, nevertheless, may not always be able to get detailed building specifications to identify the correct set-points and schedules, or to choose an alternative simulation software. The information contained in weather datasets are, however, completely out of the control of the person in charge of the simulation that may only assume them as a boundary condition. Unfortunately, not all the weather databases show the same level of data accuracy; moreover, they may refer to a climate that substantially changed in the last decades. The effects on building energy simulation results, played by different weather files referred to the city of Milan, is showed and discussed, highlighting the substantial performance difference depending on them.

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Keywords: weather files; dynamic simulations; energy needs; thermal comfort; future weather scenarios

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In the context of building renovations and new constructions, the objective to achieve the best comfort with minimum energy consumption is increasingly prominent. Stationary, semi-stationary and dynamic calculation methods are available for energy analyses but the growing awareness of building user needs, calls for enhancing the assessment of systems and components performance to guide the optimization of choices in the design phase [1,2]. In bioclimatic design and nearly Zero Energy Buildings (nZEB) projects, it is required to know the behaviour of the construction under the effect of specific drivers, or to explore the exact energy consumptions considering the presence of occupants and the exploitation of renewable energy sources, in order to avoid over-dimensioning of technical systems and consequent extra costs. Furthermore, there is a growing need to investigate passive techniques, to explore the potential of natural ventilation for cooling [3]. The concept of climate-adapted buildings is becoming crucial, due to the challenges launched by climate changes [4]. Moreover, building certification schemes provide incentives in terms of extra points when the optimization of building performance is carried out adopting advanced simulation tools. Building performance energy simulation software helps answering some of these requests, providing many information on how the building and its technical systems respond to different (indoor and outdoor) drivers.

The reliability of energy simulations depends, however, on many factors, such as the quality and detail of the model itself, the uncertainties linked to weather databases, the in-field measured parameters, and the parameters obtained from existing documentation [5,6]. Sensitivity analyses and calibration are essential tools to improve the accuracy, as confirmed by literature [7,8], nevertheless they cannot remove all the uncertainties, especially those implicit in the data source. Among the uncertainty factors, some researchers started investigating the effect of weather data quality on the final output of energy simulations. The creation of a more reliable building model is associated both to the choice of the most adequate weather dataset, which better represents the existing or future weather scenario [9-12] and to the construction method of the typical meteorological year, which requires continuous studies and improvements to overcome the limitations of the older methods [13-15].

The work summarised in the present paper, focuses on the effects that a not-adequate weather dataset may have on the analysis output of building energy simulations, that, to be reliable, should be coherent with the local climate changes experienced in the last decades. Nine of the ten warmest years on record have occurred since 2000 [16], showing their effects at a global and at a local scale. It is clear that a substantial underestimation of summer thermal loads and comfort conditions may occur, if a weather file based on data recorded more than half century ago is used.

Summer comfort is still poorly considered by the average design practice in Italy and EU, especially in the case of energy renovation of buildings for low-income families (e.g. social housing), where the attention is essentially placed on the energy savings for heating. However, the indoor environmental conditions of the buildings affect health, productivity and comfort of the occupants also during the cooling season, and may enhance or decrement people's wellbeing. Moreover, inadequate weather datasets may determine the overestimation of thermal loads during the heating season, and the consequent oversizing of technical systems. This may in the end, determine extra costs, lower efficiencies, and a higher energy consumption.

Using the energy retrofit of a public social housing unit in Milan as a reference study, in this paper we do compare the energy needs for space heating and cooling and the summer comfort conditions resulting from an energy model run with different weather datasets. Some of them, still commonly used, have been developed on the basis of weather data gathered between the 1950s and 1970s, other ones, instead, refer to data from recent years. Moreover, the mechanism of activation of shading devices and the schedule of bypass activation for ventilation, which can be both defined as a function of weather data, are investigated in detail, in order to offer a more comprehensive interpretation of the role played by weather datasets on building energy simulation outputs.

Nomenclature

TMY	Typical Meteorological Year
HDD	Heating Degree Day
CDD	Cooling Degree Day

2. Comparison of different weather datasets

Currently five different full year weather datasets are available for the area of Milan, based on measurements from several years. The datasets provide hourly values, measured or calculated, of the parameters needed to run the energy simulations, such as dry-bulb temperature, dew-point temperature, relative humidity, atmospheric pressure, wind direction and speed, global and diffuse horizontal radiation, direct normal radiation, total sky cover, etc. For energy simulations, it's usually better to use typical meteorological year (TMY)-type weather datasets, a set of meteorological data with values for every hour in a year for a given geographical location which are selected from hourly data in a longer time period (normally 10 years or more) since no single year can represent the typical long-term weather patterns [17,18].

MI_Linate_1951-1970 (Latitude 45°26', longitude 9°17', height 103 m) refers to the dataset Gianni De Giorgio (IGDG) and is based on a 1951-1970 period of record, therefore it is a typical year calculated on a base of 20 years. The data have been recorded from the weather stations of the Meteorological Service of the Italian Air Force. Measured data are: dry-bulb temperature, wind speed, relative humidity, sun hours available per day. The global horizontal radiation is available from 1958.

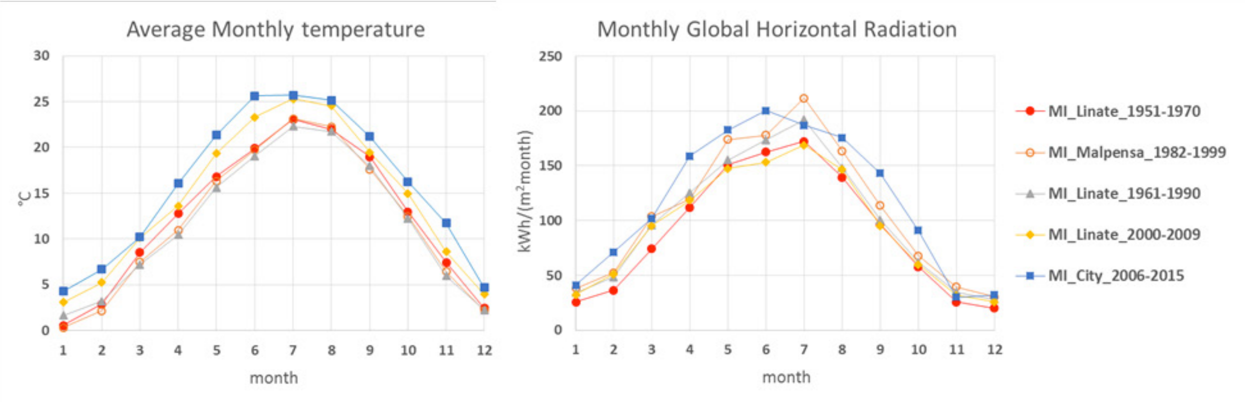
MI_Malpensa_1982-1999 (Latitude 45°62', longitude 8°73', height 211 m) refers to the International Weather for Energy Calculations (IWEC) and is the result of ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information. In these databases, the files are derived from up to 18 years (for most stations) of DATSAV3 hourly weather data originally archived at the U. S. National Climatic Data Center. The database contains weather observations on average at least four times per day of wind speed and direction, sky cover, visibility, dry-bulb temperature, dew-point temperature, atmospheric pressure and liquid precipitation. The weather data are integrated by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information.

MI_Linate_1961-1990 and MI_Linate_2000-2009 (Latitude 45°43', longitude 9°28', height 103 m) data are extracted from the meteorological database Meteonorm [19,20]. Using the software, surrounding weather stations are searched and their long-term monthly means are interpolated to the specified location. Then a stochastic weather generator creates on the basis of the interpolated monthly data, an average year with hourly resolution for most of the output formats. Measured parameters are: dry-bulb temperature, dew point temperature, precipitation, effective sunshine duration. Measured global horizontal radiation and wind speed are available for the period 1991-2010.

MI_City_2006-2015 (Latitude 45°47', longitude 9°19') weather file refers to the Joint Research Centre (JRC) database. The solar radiation data used in this weather file have been calculated from satellite data thanks to the Satellite Application Facility on Climate Monitoring (CM SAF) collaboration. All other data have been taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-interim, a global atmospheric reanalysis from 1979, continuously updated in real time. Dry-bulb temperature data have been corrected for elevation. The selection of the months for the typical year is done using the method described in the international Standard ISO 15927-4 [21]. The selection is done based on dry-bulb temperature, global horizontal radiation and relative humidity.

Weather files have been contrasted in terms of average monthly temperature, monthly global horizontal radiation, Heating Degree Day (HDD) and Cooling Degree Day (CDD), calculated according to ISO 15927-6:2007 [22] considering the heating season (for Milan it is from 15 October to 15 April) and a typical cooling season (from 1 June to 15 September). The trend of temperatures and radiation (Fig.1) presents similar distributions among the different files, with an average variation between the two extreme conditions of about 5 °C and 30 kWh/(m^2 month) respectively. Besides, in Fig. 2 it is possible to notice the correspondence between the increment of CDD (right) and the relative decrement of HDD (left), in the weather files, especially for the datasets referred to the recent years.

In the following sections, we will present the results of the energy simulations, carried out using the software EnergyPlus and comparing the two extreme weather datasets, which correspond to the weather files that describes the coldest winter (MI_Linate_1951-1970) and the one characterized by the warmest summer (MI_City_2006-2015). These two datasets represent respectively the typical meteorological year based on the oldest and the most recent data period available, outlining the warming trend registered in Milan.



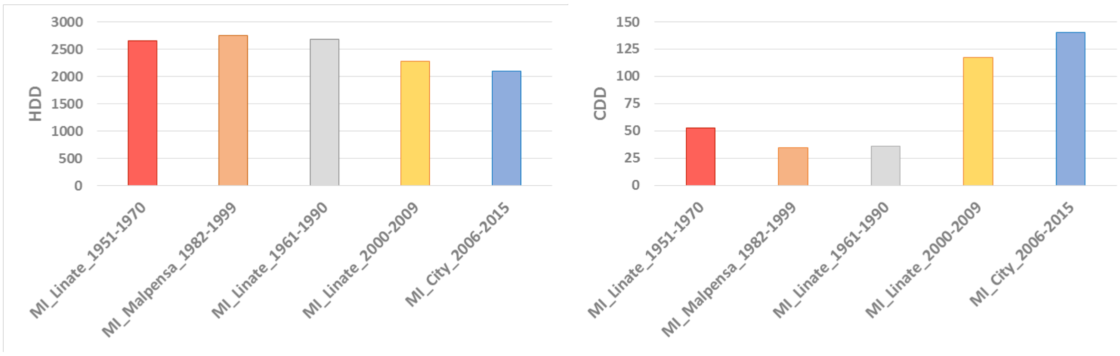


Fig.1. Average monthly temperature (left) and monthly global horizontal radiation (right) for the five different weather files

Fig. 2 HDD (left) and CDD (right) distributions for the five different weather files

3. Results

The analysis focuses on a case study of a public social housing block located in Milan, consisting of two L-shaped buildings with four stories each and a total of 66 flats. Social housing represents an important share of the public building stock; most of these buildings were built in the 70s and 80s, and have never been renovated, requiring therefore a quick and substantial retrofit.

As part of the Sharing cities project [23], the Municipality of Milano has thus decided to promote the deep energy renovation of this block, whose building envelope is made of prefabricated concrete elements, presenting almost no thermal insulation, and of low performance windows with no solar shading. The existing centralized heating system is supplied by fuel oil, whereas domestic hot water is provided by single gas boilers placed in each flat. The interventions aim to improve primarily the energy performance of the building envelope: exterior insulation of the opaque elements including walls, roof and exposed ground floor slab, low-e double glazing windows and frame with thermal break, and exterior solar shadings. In order to control heat loss due to ventilation, allowing for an adequate level of indoor air quality (IAQ), a centralized mechanical ventilation system with heat recovery and by-pass to allow for free cooling in summer and mid seasons, will be installed. The renovation of the technical systems will include the installation of a high-performance centralized heating unit based on heat pumps, used also for domestic hot water generation and LED lighting systems in common areas. The remainder final energy use will be partially complemented exploiting renewable energy.

After the analysis of existing documentation and several in-field inspections to assess the actual conditions and the technical performance of the building envelope and service systems, a dynamic energy model of the block has been prepared to support the retrofit design in terms of energy efficient choices considering energy performance, comfort, and costs optimization. The model presents a high number of thermal zones, in order to evaluate the retrofit effects at the flat level, and, in some cases, to reach the level of detail of the single room. To improve the accuracy, different schedules for occupancy and operable components have been studied and developed.

Among the different aspects, the project of solar shading devices in the dynamic model deserves particular attention because its control can substantially affect building thermal and lighting performance both from an energy and comfort point of view [24]. Solar shading systems influence daylight levels in a building; they control solar gains and affect the thermal exchange through the glazed building envelope. Several studies [25] about the shadings' effect on yearly energy use demonstrated that shading devices may decrease the cooling requirements, but at the same time, they may increase the heating demand, due the reduction of solar gains during the heating season. In EnergyPlus settings, the function Shading Control Types allows to specify a schedule that determines when the control is active. It can be seasonal, when the incident solar radiation is high enough, or it can be set on fixed period, or depending on other drivers such as outdoor air temperature or glare, etc. After a sensitivity analysis, the activation of the shading device in the model has been set for values of irradiance, on the component' surface, higher than 200 W/m^2. Similarly, for the mechanical ventilation system with heat recovery, the activation of the by-pass function has been fixed depending on the weather conditions; from May to September, all day long, when external dry bulb air temperature is between 13 °C and 26 °C the by-pass is on. The model is characterized by a centralized mechanical ventilation system, therefore has not been possible to implement control algorithms for bypass activation that consider the indoor air temperature of every thermal zone.

Dynamic simulations allowed evaluating the best strategies of intervention for the opaque envelope and the glazed surfaces to reduce the energy need for heating. A total 32 different scenarios have been studied in order to find out the best solution in terms of energy need for heating and costs (Fig. 3). A further series of simulations was then performed, to assess indoor comfort levels during the cooling season for the best scenario according to heating and costs analysis.

		EXTERIOR INSULATION FINISHING SYSTEM				ATTIC				BASEMENT		BALCONIES STAIRCASE		WINDOWS	
		Mineral wool								PIR10cm/Phenolic Resin10cm		PIR14cm/Phenolic Resin10cm		4+4.2/16/3+3.1 Low-E 4+4.4/16/4 Low-E	
		15 cm	20 cm	25 cm	30 cm	15 cm	20 cm	25 cm	30 cm						
●	15PP	0.195				0.249				0.225		0.148		1.653	
●	20PP		0.152				0.190			0.225		0.148		1.653	
●	25PP			0.125				0.156		0.225		0.148		1.653	
●	30PP				0.106				0.129	0.225		0.148		1.653	
■	15RP	0.195				0.249					0.186	0.148		1.653	
■	20RP		0.152				0.190				0.186	0.148		1.653	
■	25RP			0.125				0.156			0.186	0.148		1.653	
■	30RP				0.106				0.129		0.186	0.148		1.653	
▲	15PR	0.195				0.249				0.225			0.163	1.653	
▲	20PR		0.152				0.190			0.225			0.163	1.653	
▲	25PR			0.125				0.156		0.225			0.163	1.653	
▲	30PR				0.106				0.129	0.225			0.163	1.653	
◆	15RR	0.195				0.249					0.186		0.163	1.653	
◆	20RR		0.152				0.190				0.186		0.163	1.653	
◆	25RR			0.125				0.156			0.186		0.163	1.653	
◆	30RR				0.106				0.129		0.186		0.163	1.653	
○	15PPs	0.195				0.249				0.225		0.148			1.100
○	20PPs		0.152				0.190			0.225		0.148			1.100
○	25PPs			0.125				0.156		0.225		0.148			1.100
○	30PPs				0.106				0.129	0.225		0.148			1.100
□	15RPs	0.195				0.249					0.186	0.148			1.100
□	20RPs		0.152				0.190				0.186	0.148			1.100
□	25RPs			0.125				0.156			0.186	0.148			1.100
□	30RPs				0.106				0.129		0.186	0.148			1.100
△	15PRs	0.195				0.249				0.225			0.163		1.100
△	20PRs		0.152				0.190			0.225			0.163		1.100
△	25PRs			0.125				0.156		0.225			0.163		1.100
△	30PRs				0.106				0.129	0.225			0.163		1.100
◇	15RRs	0.195				0.249					0.186		0.163		1.100
◇	20RRs		0.152				0.190				0.186		0.163		1.100
◇	25RRs			0.125				0.156			0.186		0.163		1.100
◇	30RRs				0.106				0.129		0.186		0.163		1.100

Fig.3. Summary of the 32 different combinations evaluated for identifying the best solution of retrofit intervention on the building envelope, in terms of energy need for heating and costs. Values in the table are U-values [W/m^{2}K] of the considered component. The case underlined in figure (25PP) corresponds to the best scenario according to heating and costs analysis

3.1. Energy results

Figure 4 shows the results of the 32 simulations in terms of energy need for heating versus capital cost of the retrofit interventions (envelope only), comparing the two weather files as discussed above: MI_Linate_1951-1970 (left) and MI_City_2006-2015 (right). The energy need for heating, according to EN 15603:2008 [26] is defined as the heat to be delivered to a conditioned space to maintain the intended temperature conditions during a given period of time. In the energy simulations, and in compliance with Italian legislation, the indoor air temperature was set at 20°C as set point during the whole heating season 15/10-15/04.

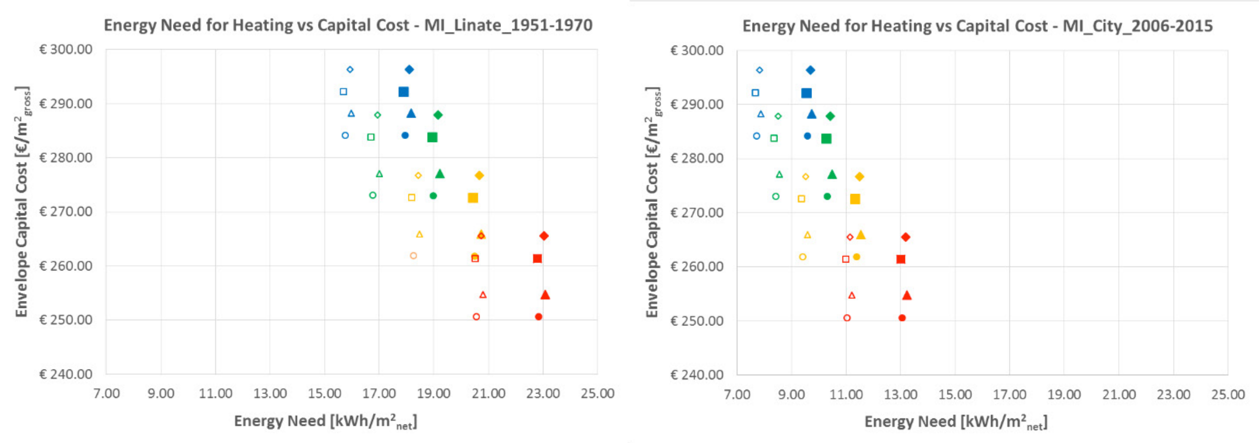


Fig. 4. Distribution of the 32 alternatives of retrofit intervention for the two extreme climate datasets: MI_Linate_1951-1970 (left), MI_City_2006-2015 (right)

Results show a similar distribution, but it is evident the decrease of energy need for heating when adopting the MI_City_2006-2015 weather file. Results based on the dataset MI_Linate_1951-1970 (fig. 4, left), whose outdoor temperatures are colder, show a range of 15-23 kWh/m$^2_{net}$. Whereas, by using the MI_City_2006-2015 weather file (fig. 4, right), whose outdoor temperatures are slightly warmer, the results are distributed between 7 and 14 kWh/m$^2_{net}$, with a reduction of more than 40% in terms of energy need.

3.2. Comfort results

Comfort evaluations have been performed in reference flats according to the standard EN 15251 approach [27]. Acceptable summer indoor conditions have been assessed as a function of the outdoor running mean temperature, defined as the exponentially weighted running mean of the daily outdoor temperature, and the indoor operative temperature. Figure 5 shows the model of one of the buildings and it highlights, as an example, one of the flats in which the analysis of acceptable indoor conditions has been carried out. In general, the output of the analysis should be used for the design of passive solutions to prevent overheating during the cooling season, e.g. solar shadings and massive elements.

Figure 6 reports, in particular, the results referred to the scenario 25PP (see Fig.3), which is characterized by 25 cm of exterior insulation in mineral wool, insulations of the basement, balconies and staircases with Polyisocyanurate Insulation Foam (PIR) panels, low-e double glazing with laminated glasses. No mechanical cooling system has been considered, as planned in the project. The internal heat gains such as the ones depending on occupants, appliances and lighting systems, are taken into account in the simulations, according to an imposed schedule. The results provide information on the periods in which the building might potentially work in free-running mode with optimal comfort conditions, and the frequency and intensity of overheating periods.

Figure 6 shows the distribution of indoor operative temperature for the two reference weather datasets so far adopted; the set of parallel lines defines four categories, according to the standard EN 15251. The hourly indoor operative temperature is compared to the comfort thresholds for Categories I, II and III for the warm period of the year. The analyses provide the fraction of time during which the indoor operative temperatures are distributed in the different categories or exceed the given thresholds that depend on the chosen comfort category (Table 1).

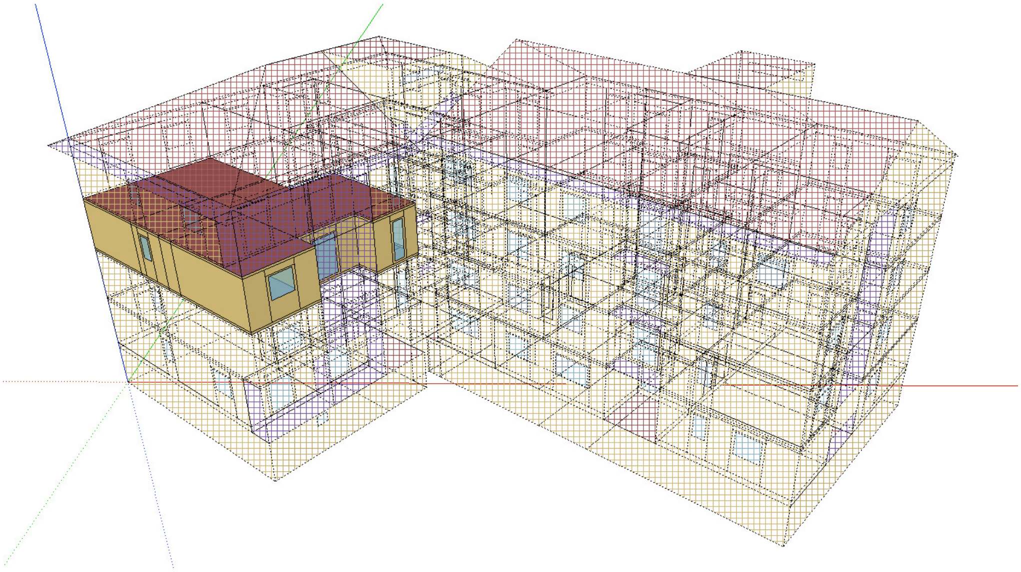


Fig. 5 Geometric model of one building highlighting the flat considered for comfort analysis

The graphs show that under post-retrofit and free-floating conditions, the flat does not show relevant overheating issues, when simulations are performed with the coldest weather file MI_Linate_1951-1970 (Figure 6, left). However, when the MI_City_2006-2015 dataset is applied (Figure 6, right) the overheating conditions substantially increase, and the number of hours with comfort condition decreases. Considering the percentages inside the different categories, Table 1 shows a decrease of values belonging to category I (from 74.6 % to 19.3 %), category II (from 97.0 % to 65.3 %) and category III (from 100 % to 97.9 %). This underlines the necessity to reserve greater attention to the choice of current and future weather datasets in simulations in order to be effectively able to assess the effects of design on comfort conditions during the cooling season.

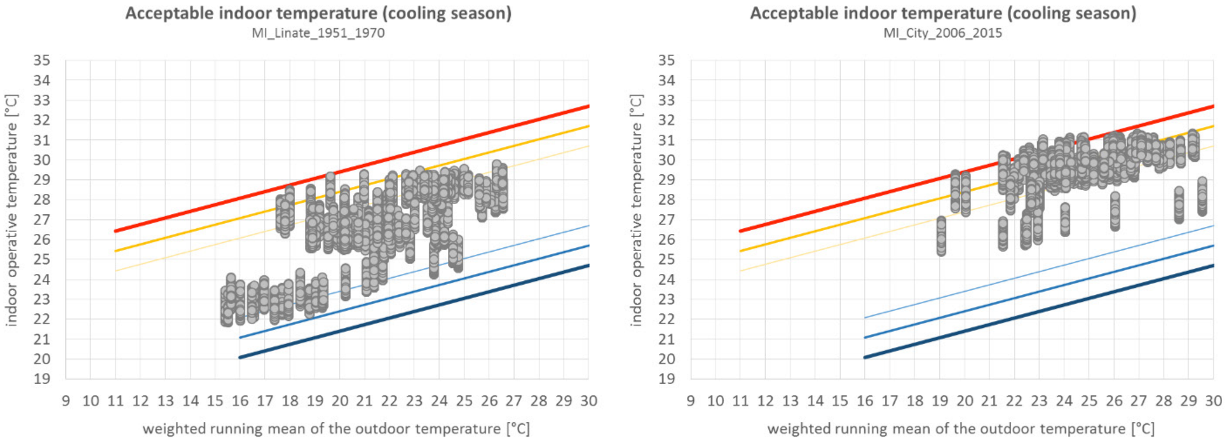


Fig. 6 Hourly distributions of the indoor operative temperature for a flat without mechanical cooling systems as a function of the outdoor running mean temperature: MI_Linate_1951-1970 (left) and MI_City_2006-2015 (right)

Table 1. Percentage of time during which the indoor operative temperatures are in or out of the different categories, according to the standard EN 15251 [27]. The results are referred to the simulations of the case 25PP (see Fig. 3) without mechanical cooling system.

	MI_Linate_1951-1970		MI_City_2006-2015		
	% in	% out	% in	% out	
cat I	74.6 %	25.4 %	19.3 %	80.7 %	including the shading device operation
cat II	97.0 %	3.0 %	65.3 %	34.7 %	
cat III	100 %	0.0 %	97.9 %	2.1 %	
cat I	60.0 %	40.0 %	10.7 %	89.3 %	without the shading device operation
cat II	86.9 %	13.1 %	13.5 %	86.5 %	
cat III	98.8 %	1.2 %	49.6 %	50.4 %	

Results reported in Table 1, show the effect of the activation of solar shading devices on the indoor comfort during the cooling season. Although the role of solar shading in improving comfort is obvious, the values reported in the table show that its effect may be massive in the climate of Milan. Moreover, Table 1 also reveals that the use of different weather files may have a much higher impact on the simulation results of a building without solar shading, than of a building provided with it. The results highlight the necessity to activate solar protections especially when a dataset based on values gathered in recent years is chosen, i.e. the MI_City_2006-2015 weather file. It means that if old datasets are adopted, the need for a proper solar shading control may be substantially underestimated.

Similar analyses have been performed for the mechanical ventilation system with heat recovery, to underline the importance of activating a by-pass during the hottest period of the year. Comfort condition substantially decreases if the by-pass option is not activated during the warm season. In particular, when using MI_City_2006-2015 weather file it is observable a reduction of the fraction of time in category I from 19.3 % to 9.0 %, in category II from 65.3 % to 12.1 % and in category III from 97.9 % to 29.3 %.

3.3. Energy need for space heating and cooling

In order to quantify the effect of the different weather datasets, the monthly and yearly energy need for heating and cooling of the whole block, i.e. the two buildings, has been calculated (Fig. 7), simulating an ideal active cooling system to maintain an indoor set-point temperature of 26 °C during the cooling season.

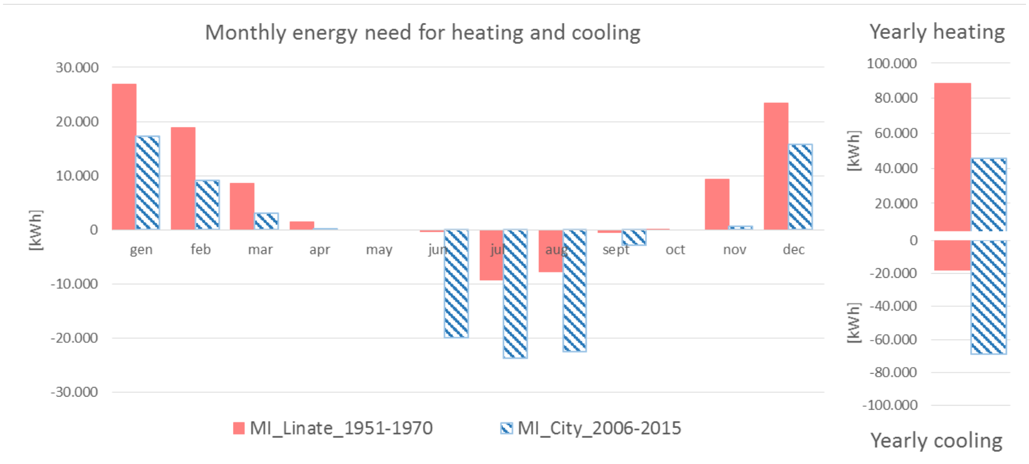


Fig. 7 Monthly (left) and yearly (right) energy need for heating and cooling according to MI_Linate_1951-1970 dataset (in red) and MI_City_2006-2015 weather file (diagonal hatch in blue)

The more challenging conditions reported by MI_City_2006-2015 dataset (diagonal hatch in blue), lead to a higher energy need for cooling, if compared to the energy need evaluated with MI_Linate_1951-1970 (in red). The yearly energy need for cooling passes, indeed, from 18 MWh to 69 MWh. This variation is more significant than the decrease of the yearly energy need for heating registered as function of the two different weather datasets, i.e. from 88 MWh to 46 MWh.

4. Discussion

The paper showed the substantially different energy and comfort performance results, obtained by dynamic simulation, as function of two different weather datasets currently available for researchers and professionals. These weather datasets were selected because they are used in the common practice and are based upon measured historical data belonging to different time ranges. The paper shows that just using different historical data, energy simulation results may be substantially different, and thus guide the building design to different choices. The issue becomes even more relevant if future evolutions of the weather are considered, by means of the adoption of future weather files, as already done for the climate of Milan, in the analysis of a child care centre [9]. In the mentioned work, by adopting the approach presented by Jentsch et al. [28], the tool called CCWorldWeatherGen was applied to provide hourly future weather data. The tool specifies that ideally the EPW files used for the 'morphing' process should be formed of weather data derived from measured parameters of the years 1961-1990 in order to match the HadCM3 reference timeframe. Moreover, the reference interval should cover a period of 30 years. Therefore, the morphing approach cannot be applied to the more recent and challenging dataset (MI_City_2006-2015) without incurring in major errors. We limited the application of the tool to the dataset showing more coherence with the mentioned limitations, i.e. MI_Linate_1951-1970, visualizing three future scenarios: 2020, 2050, 2080 (fig. 8). The 2080 scenario appears as challenging as the MI_City_2006-2015, which is based on real measured data from the last decade. This shows that even for future weather analysis the choice of the original dataset to be used in the morphing process is a crucial element in terms of reliability of outputs.

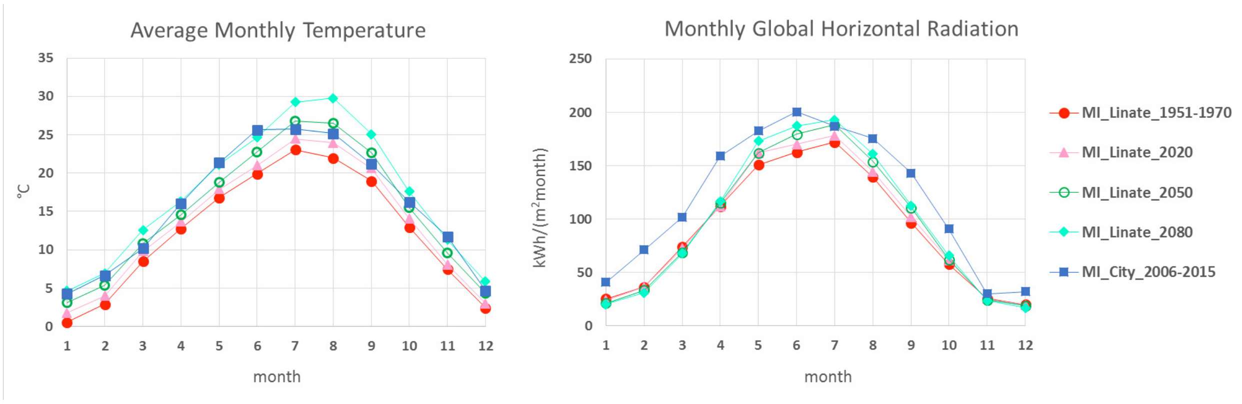


Fig. 8 Comparison of average monthly temperature (left) and monthly global horizontal radiation (right) for three future scenarios (2020, 2050, 2080) generated from MI_Linate_1951-1970 dataset (red dots)

5. Conclusion

By adopting the case study of an energy retrofit for a public social housing in Milan, the paper showed that the choice of an appropriate weather dataset is very significant if different retrofit scenarios should be compared, both in terms of energy savings and of thermal comfort (especially during the cooling season). The performed simulations report a substantial increase of the yearly energy need for cooling, if a weather dataset based on recent years is adopted. Moreover, the comparison with future weather scenarios developed on historical data (1951-1970), showed that weather files derived from data of the last decade are already quite similar to projection for 2080. It depends on the quality and reliability of the datasets used for the morphing procedure that should not be too old.

It is clear the urgency to update the available reference weather files according to the global and local warming trends registered in the last decades and the strong demand of a standardized reference to create an official shared

TMY database for the different world locations, to reduce the gap between buildings' simulated and real performance.

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