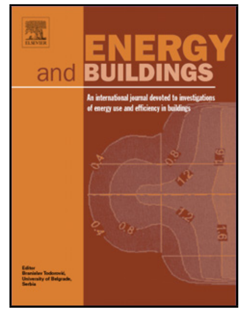

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Energy retrofit for a climate resilient child care centre

Lorenzo Pagliano[1], Salvatore Carlucci[2], Francesco Causone[1], Amin Moazami[2*] and Giulio Cattarin[1]

[1] *end-use Efficiency Research Group, Department of Energy, Politecnico di Milano, Via Lambruschini 4, 20156, Milano, Italy*

[2] *NTNU Norwegian University of Science and Technology, Department of Civil and Transport Engineering, Trondheim, Norway*

[*] *Corresponding author. Tel.: +47 40 476 475. E-mail address: amin.moazami@ntnu.no.*

Abstract

Climate scientists have developed and refined climate change models on a global scale. One of the aims of these models is to predict the effects of human activities on climate, and thus the delivery of information that is useful to devise mitigation actions. Moreover, if they can be properly downscaled to a regional and local level, they might be useful to deliver support for adaptation actions. For example, they may be used as an input for the better design of the features of buildings in order to make them resilient to climate modification, e.g., able to passively control heat flows to produce comfortable indoor conditions not only in the present climate, but also in future climate conditions. Taking into account the future weather scenarios that show an increase in the global temperature and climate severity, a likely consequence on building energy use will be a substantial shift from space heating to space cooling, and potentially uncomfortable thermal conditions during the summer will became a major challenge, both for new and existing buildings. In this paper, a deep energy retrofit of a child care centre located in Milan (Italy) is analysed on the basis of future weather scenarios; the analysis aims to identify to what extent choices that are made nowadays on the basis of a typical meteorological year may succeed to provide acceptable energy and indoor environmental performance throughout the future decades. The analysis confirms that climate change might require the installation of active cooling systems to compensate for harsher summer conditions over a long-term horizon, however, in the mid-term, passive cooling strategies combined with envelope refurbishment may still guarantee thermally comfortable conditions, and they will reduce cooling needs when active cooling is eventually installed.

Keywords

Climate change, climate change adaptation, climate resilience, energy retrofit, future weather scenarios, resilient building

Abbreviations

ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; CSI, Climatic Severity Index; CO_2, Carbon dioxide; CDD, Cooling Degree-Days; HDD, Heating Degree-Days; GCM, General Circulation Model; GCSI, Global Climate Severity Index; HadCM3, UK Met Office Hadley Centre Coupled Model version 3; HVAC, Heating Ventilation and Air Conditioning; IAQ, indoor air quality; IPCC, Intergovernmental Panel on Climate Change; NASA, National Aeronautics and Space Administration; NOAA, National Oceanic and Atmospheric Administration (USA); TMY, Typical Meteorological Year; TRY, Typical Reference Year; IGDG, Italian Climatic data collection "Gianni De Giorgio"

1 Introduction

The average temperature of our planet is increasing rapidly. According to the analysis performed by NASA in 2015, the year 2014 was the warmest on record (since 1880), and this trend is expected to continue over the long term [1]. At the beginning of 2016, NOAA and NASA reported that 2015 was by far the hottest year on record globally. NOAA [2] also reported that "During December [2015], the average temperature across global land and ocean surfaces was 2.00 °F (1.11 °C) above the 20th century average. This was the highest for December in the 1880-2015 record, surpassing the previous record of 2014 by 0.52 °F (0.29 °C). The December temperature departure from average was also the highest departure among all months in the historical record and the first time a monthly departure has reached +2 °F from the 20th century average". The working groups of the Intergovernmental Panel on Climate Change (IPCC) have developed scenarios for both contaminant emissions and global warming [3,4]; these scenarios are able to describe the likely average global conditions in the future. However, local climate scenarios are required in order to design our built environment to be able to withstand future weather conditions. ASHRAE fundamentals 2009 states in Chapter 14: "The evidence is unequivocal that the climate system is warming globally (IPCC 2007). The most frequently observed effects relate to increases in average, and to some degree, extreme temperatures" [5]; and it reports the results obtained by Thevenard [6] according to which design conditions, heating degree days and cooling degree days were all found to have significantly modified values.

By adopting the *morphing* methodology presented by Belcher et al. [7], three different future weather scenarios were developed for the city of Milano, and the deep energy retrofit design of a child care centre [8,9] was assessed against them, in order to evaluate the building resilience to future local climate change.

2 Background

The Italian educational buildings stock consists of 52 000 buildings, of which about 63 % were constructed before 1973 [10], the year of the first oil crisis, which provided the initial *stimulus* towards the introduction of energy efficiency targets in building regulations. The energy retrofit of such a large and old building stock, which is mostly owned by local governments, can yield significant improvements in energy efficiency (EE). Constructions from before the first Italian law on energy performance in buildings (Law n. 373/1976), especially in the 50's and 60's, are characterised typically by a very poor performance. Hence, the case study presented in this paper, the retrofit of a building that was constructed in the 80's, might provide a conservative estimation of the energy savings that could potentially be obtained if a similar retrofit strategy were applied to buildings constructed between the 50's and 70's. However, also the envelope of the pre-retrofit child care centre, analysed here, presents a poor thermal performance, as indicated in Table 1.

Educational buildings capable of high energy performance have been built in the last decades, sometimes showing problematic issues on the side of thermal comfort (TC) and indoor air quality (IAQ) [11]. For example, higher ventilation rates in order to improve IAQ imply more energy use, and care in design and control is needed to find a sensible balance. A potential 'EE-TC-IAQ dilemma' in high-performance educational buildings in the Netherlands has been analysed through measurements and surveys and it is presented in [12].

Another challenge is that even high-performance buildings and zero-energy buildings are designed using current or historical data such as typical weather data files e.g. Typical Reference Year (TRY), Typical Meteorological Year (TMY) and, in the case of Italy, weather files of the Italian Climatic data collection "Gianni De Giorgio" (IGDG), all of which are based on weather data parameters measured in a time span of the order of twenty years in the past [13]. This results in a lack of analysis of the behaviour of those buildings during their lifetime where climate patterns might be significantly different from present and past patterns. In order to contribute in filling this gap, this paper focuses on the resilience assessment of a high-performance retrofit for a child care centre against future weather scenarios. To achieve this aim, in parallel to an analysis of energy performances, the long-term thermal discomfort indices proposed in the European standard EN 15251 [14] are used to assess the indoor thermal comfort conditions, and suitable climate severity indices have been applied to characterise the severity of a few future weather scenarios.

2.1 Climate severity

Phillips and Crowe [15] define climate severity as “an unfavourable aspect of climate that arises as a consequence of certain adverse climate elements, occurring either singularly or in combination, and persisting beyond some minimum duration and/or at an intensity above some critical threshold”. It was also pointed out that “duration, frequency, extremes and variability are important statistics that should be considered part of any scheme that attempts to quantify the unfavourable aspects of climate” [15]. One of the first examples is the *Climatic Severity Index* (CSI) that was proposed by Markus et al. [16], which defines, by a single number on a dimensionless scale, “the stress placed on a building’s energy system by any given climatic *stimulus*”.
For the specific case of buildings, the climate severity can be expressed in various ways. A particularly simple way is by using the *Heating degree-days* (HDD) *index*, i.e. the cumulative number, computed over a year under ‘representative’ weather, of the products of a time interval (a day) and the sole positive difference between an outdoor reference temperature (below which a building needs to be heated[1]) and the outdoor air temperature. In case a conventional value for the *building balance-point temperature* is assumed, e.g., 18 °C in Europe and 65 °F in the USA, the number of HDDs becomes independent of the features of the building and can be used as a concise description of the cold season climate; it is often used for climatic classification purposes in legislation [17]. The great diffusion of mechanical cooling systems fostered the definition of a similar index for the warm season, i.e. the *cooling degree-days* (CDD). However, not all of the national legislations have included a classification of climatic zones for cooling needs [18]. The heating and cooling degree-days, based on a conventional choice of the building balance-point temperature, have the advantage of being independent from the specific building features and being easily available, see e.g., [19]. Caution should be used anyway, and one should check how the tabulated values are calculated for both the reference temperature and the time step for calculations (hourly, daily) [20], since these may differ from country to country. Moreover, degree-days cannot capture the dynamic effects due to solar irradiance (excluding the indirect effect on external temperature), which depend on many factors including the building’s orientation, the window-to-wall ratio, the optical properties of the glazing systems (including fixed/movable solar shading devices), the thermal mass of the building etc. Thus,

[1] This temperature is called the *building balance-point temperature* and it is defined as the value of the outdoor air temperature at which, for a specified value of indoor temperature (set-point), the total heat loss is equal to the free heat gain (from occupants, lights, sun etc.). The building balance-point temperature is a consequence of the functions and features of the building rather than just the outdoor weather conditions.

degree-day analysis can lead to large deviations when compared to energy simulations [21]. More detailed methods have been developed in order to include the building thermal dynamics during the whole year in a single value metric. For example, Burmeister and Keller [22] and Keller and Magyari [23] propose an ordinary differential equation for an energy balance of the indoor air temperature, which includes information on the thermal mass, the thermal transmittance of the external walls, the air change rate and the total solar energy transmittance of transparent elements, condensed into three parameters named the *generalized loss-factor*, the *time constant* and the *gain-to-loss ratio*. The equation also includes a building-specific meteorological function, which depends on the external air temperature, the solar irradiance on the façade and the gain-to-loss ratio. The model allows for the calculation of the free-running temperature of a room, and it helps when making decisions at an early-design stage, when it is still not possible or desirable to handle a large number of parameters. The objective is to "arrive at the lowest possible energy consumption of a room, construct it in a way, that its free-run-temperature[2] remains the most part of the year within the comfort range […]. This strategy minimises not only the energy need but also the peak powers needed for heating and/or cooling" [23].

In recent years, an Italian research group led by Terrinoni developed a new index that tackles the climate severity of the summer season [18,24,25]. The proposed *Summer CSI* is determined from hourly calculations and takes into account the outdoor air temperature, specific humidity and solar irradiation. The energy requirement for cooling a space is normalised with respect to the main characteristics of the building (geometrical dimensions, global thermal transmittance and thermal capacity), thus being independent from the characteristics of the building, and linearly dependent on the climatic variables.

In the study by Sánchez et al. [26], the climate severity metrics for winter and summer were assessed as the ratio between the heating or cooling energy needs of a certain building and the needs that the same building has in a reference site. The indices are functions of the heating or cooling degree-days and the mean accumulated global radiation over a horizontal surface. The methodology was developed in particular for assessing the influence of the *urban heat island* effect on a building's energy use. With a similar definition, Salmerón et al. [27] introduce the *Global Climate Severity Index*, combining the heating and cooling end-uses and weighting them in terms of primary energy and of carbon dioxide (CO_2) emissions.

2.2 Building resilience to future weather scenarios

The CSI and its following modifications were introduced to assess the performance of a building in the typical climate, however, as the consequences of climate change become more and more evident at a local level, the research interest now includes a medium-to-long-term perspective. Given the lifetime of a building, predictions show that it will experience substantial climatic change, and thus modelling for design and compliance to national guidance should be completed using both typical and future weather scenarios [28]. Although de Wilde and Tian [29] remarked that the HVAC systems are likely to be replaced every 15-20 years, a time span in which the gradual effects of climate change might not yet play a relevant role, this is only true for the generation components of those systems. Distribution and terminal devices usually have a longer life; the life of opaque and transparent building envelope elements are generally even longer, and the latter elements should, hence, be dimensioned to be able to perform their function in future climate scenarios.

[2] Note of the authors: usually the *free-run-temperature* mentioned here is generally called *free-running temperature* in the literature.

Throughout the last decades, researchers have proposed various ways to assess how buildings will react to climate. As pointed out in [28], "the overwhelming majority of studies on the impact of climate change on buildings thus far look at relatively straightforward performance indicators: energy use for heating, energy use for cooling, and building overheating. Both energy uses are often combined into one figure for overall energy use, or annual carbon emissions".

Two main approaches can be followed, which could be denominated general and building-specific.

The former proposes indices that are not strictly related to the analysed building and rely on simple correlations and the global thermal performance parameters of buildings. For example, Burmeister and Keller [22] trace back the thermal behaviour of a room to three parameters: the generalised loss-factor (accounting for the heat losses through the envelope and the ventilation/infiltration rate), the time constant and the (solar) gain-to-loss ratio. The impact of these parameters can be studied without detailing, e.g. the stratigraphy of the opaque components or the optical properties of the transparent elements. The strength of this approach is evidently the attempt to gain early hints that can guide the pre-design phase of a building.

The latter focuses on the analysis of one or a few case studies or of ideal typical buildings, and it relies on dynamic thermal simulation to obtain yearly time series for present and future climate conditions. This approach needs a more detailed description of the building's characteristics, and thus it cannot be suitable in a pre-design phase. However, it can enable a deeper understanding of the thermal dynamics of specific parts of the analysed thermal system (meaning the building envelope and its services), and it may also offer insights to guide a generalisation process for a broader building stock. For example, Wang and Chen [30] analysed the change in the energy requirement for space cooling in buildings in 15 different US cities that are located in seven climate zones by the decade throughout the 2080s. In particular, the typical buildings in this study were an apartment, a hospital, a hotel, a single-family house, a small and a medium-sized office, a restaurant, a mall and a school.

Although these indices are mostly dedicated to assess energy use, they should always be accompanied by an indication of the thermal comfort levels that are expected to be experienced by the occupants, in particular when dealing with sensitive and fragile persons as e.g. handicapped, sick, very young children and elderly persons [31]. As reported in [28], "some work is emerging that suggests a need to study alternative or more refined metrics"; for example the work done by Lomas and Ji [32] that correlates resilience of passively cooled buildings to their life expectancy.

Thermal comfort assessments for the future climate cannot usually take into consideration the full spectrum of outdoor conditions, due to the inevitable inaccuracy of predictions. Probably one of the most complex thermal comfort-based index proposed so far is the *Climate Severity Index* by Murdock et al. [33,34], which comprises indicators for winter discomfort (wind chill, length of winter and severity of winter) and summer discomfort (Humidex, length of summer, warmth of summer, dampness), as well as psychological factors (darkness, sunshine, wet days and fog), hazards (e.g., strong winds, thunderstorms and snowfall) and outdoor mobility (e.g., restricted visibility). Evidently, this index was not intended to only be used for indoor thermal comfort assessments, and it has a more general focus on perceived 'weather-related' well-being. While offering a good attempt at a comprehensive evaluation of the impact of climate severity on personal thermal comfort, the index presents drawbacks, such as the need for very advanced weather predictions and the strong impact of weighting coefficients when combining factors in the global index.

In the field of indoor thermal comfort assessment, the general trend is to adopt long-term thermal discomfort metrics (e.g., [31]), such as indices that refer to thermal comfort models or simpler criteria that compute the number of hours outside certain fixed temperature ranges. In general, more than fifteen long-term thermal discomfort indices are available in literature and standards, and they can be grouped into four homogeneous categories: percentage indices, cumulative indices, risk indices and averaging indices [35]. Unfortunately, their assessment capabilities are not aligned and the selection of the index strongly influences the assessment [36]. In the present paper, the thermal resilience of a building under varying climatic conditions is evaluated by means of all-year, whole-building, and dynamic simulations; and it is expressed in terms of:

- The energy need for space heating and cooling[3] under typical and future weather scenarios.
- The indoor operative temperature in free-running conditions under typical and future weather scenarios.

3 Case study: the comprehensive energy retrofit of a child care centre

The object of the analysis is a child care centre that is occupied by children who are 3 to 36 months old. It was built in the '80s in Milan, Italy [8,9]. It is a one-story building with a simple rectangular base (44 m long and 23 m wide): the longest sides are facing south-west and north-east (Figure 1 and 2). Around 58 % of the ground floor is dedicated to children activities, and the rest is used for staff and service areas. The building has: a gross floor area of 944 m^2; a net floor area of 855 m^2; a gross heated volume of 3422 m^3 and a shape factor (S/V) equal to 0.77 m^2/m^3.

Figure 1: Southwest façade of the child care centre.

[3] The *energy need for heating or cooling* is defined in EN ISO 13790 [37] and EN 15603 [38] as "heat to be delivered to, or extracted from, a conditioned space to maintain the intended temperature conditions during a given period of time".

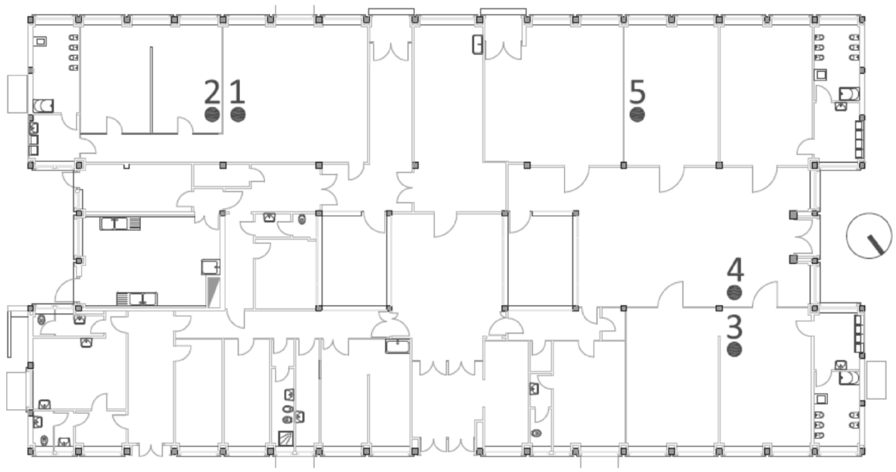

Figure 2: Building plan view including the five monitored rooms.

The existing building is a typical heavy-prefabricated facility that is made of precast concrete panels that include a thin layer of polystyrene foam. The U-value of the walls before the retrofit is estimated to be about 1.0 W/(m^2 K). After the retrofit the façade will be covered with prefabricated wooden modules. The modules are highly insulated (with approximately 35-38 cm of mineral wool) and include mechanical ventilation and automated solar shading devices. The U-value of the external walls after the retrofit will be in the order of 0.1 W/(m^2 K).

The existing roof is a pitched metallic plate with no insulation, placed upon a horizontal concrete slab (Predalles system). The U-value of the roof before the retrofit is estimated to be around 0.9 W/(m^2 K). The metallic plate will be removed and a new insulation layer will be laid on the existing slab (approximately 38-40 cm of mineral wool). After the retrofit the U-value of the roof will be in the order of 0.1 W/(m^2 K).

The existing floor has been constructed using a precast concrete slab with a linoleum finishing. The whole floor is above a basement space that is not heated. An insulation layer 10 cm to 15 cm thick will be added to the side of the slab that is facing the basement in order to reach a U-value of 0.3 W/(m^2 K).

The existing windows are made of an air-filled double glazing unit, $U_g \approx 3$ W/(m^2 K), with aluminium frames without thermal breaks, $U_f \approx 6$ W/(m^2 K). In addition to the low thermal performance, the low airtightness of the existing windows causes a high infiltration loss. During the retrofit, new high-performance windows (with an overall thermal transmittance $U_w = 0.73$ W/(m^2 K). will be integrated in the prefabricated façade modules.

A natural gas boiler for heating is currently installed in the child care centre in combination with metal radiators, whereas a connection to the local district heating system will be provided after the retrofit.

No mechanical ventilation system is currently available in the building, and the ventilation is accomplished by the manual operation of the windows. A new decentralised mechanical ventilation system coupled with highly-efficient double-flow heat recovery units with a nominal sensible recovery efficiency of 0.80 will be installed inside the prefabricated façade.

The building's indoor conditions were monitored from July 2014 to July 2015 (Figure 3 and 4), and the building envelope was checked with an infrared thermal camera. During the Christmas holidays there was a large drop in the indoor temperature, and similar rapid temperature drops appeared over winter weekends and during the night-time when the heating system was off. This is evidence of the poor thermal features of the building envelope (Figure 3).

CO_2 concentration was monitored in Room 4 (Figure 4), which is a common space where children play and spend a large part of their time. Throughout August the building is unoccupied, therefore, the recorded average value of 400 ppm may be considered as the average background outdoor CO_2 level. After September, noticeable peaks have been recorded in the room, with values that substantially exceed the reference value of 700 ppm above the background level [39], i.e. beyond 1100 ppm. This evaluation should be made under steady-state conditions, however, the recorded peaks go far beyond the threshold, showing that the building needs a better ventilation strategy.

The amount of delivered energy[4] [37,38] to heat the space and produce hot water was gathered from energy bills for the heating seasons from 2008 to 2015, showing an average yearly value (normalised with respect to the net floor surface of the treated zones) of 130 kWh/(m^2 a) for heating and 30 kWh/(m^2 a) for hot water. Delivered energy for heating shows considerable variations from year to year as a function of the different climate severities. The delivered energy in the form of electricity for the seasons from 2012 to 2014 was on average 35 kWh/(m^2 a).

The data for the delivered energy, derived from the bills and the indoor environment monitoring data, are coherent with the low thermal performance of the existing building envelope components (Table 1) and heating and lighting systems; furthermore, no solar control strategy has been implemented in the existing building, and this clearly contributes to overheating during the hot periods. Finally, the child care centre shows poor ventilation management and a potential low level of indoor air quality (IAQ).

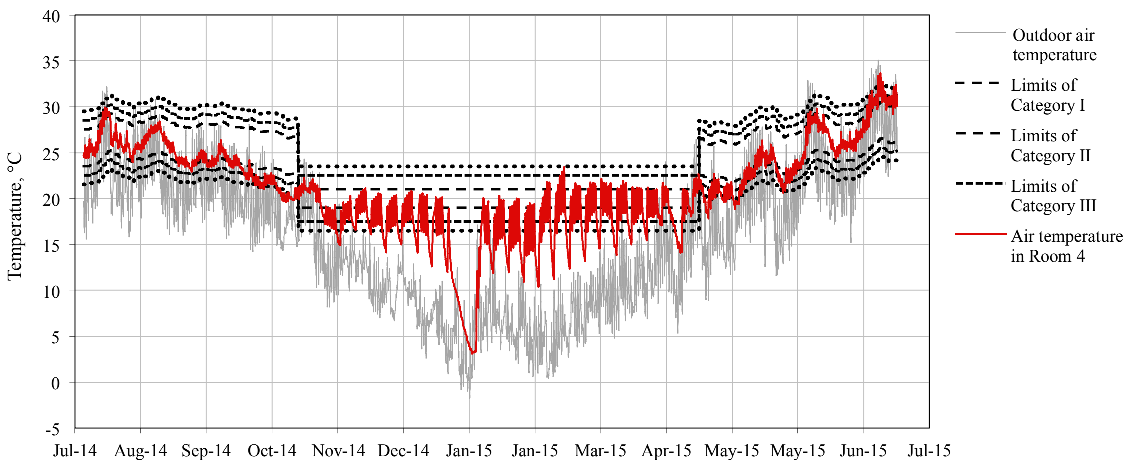

Figure 3: Outdoor air temperature and indoor air temperature in Room 4 (used as a proxy of the operative temperature) compared to the operative temperature ranges for comfort categories according to standard EN 15251.

[4] *Delivered energy* is defined in ISO 13790 [37] and EN 15603 [38] as "energy, expressed per energy carrier, supplied to the technical building systems through the system boundary, to satisfy the uses taken into account (heating, cooling, ventilation, domestic hot water, lighting, appliances etc.) or to produce electricity".

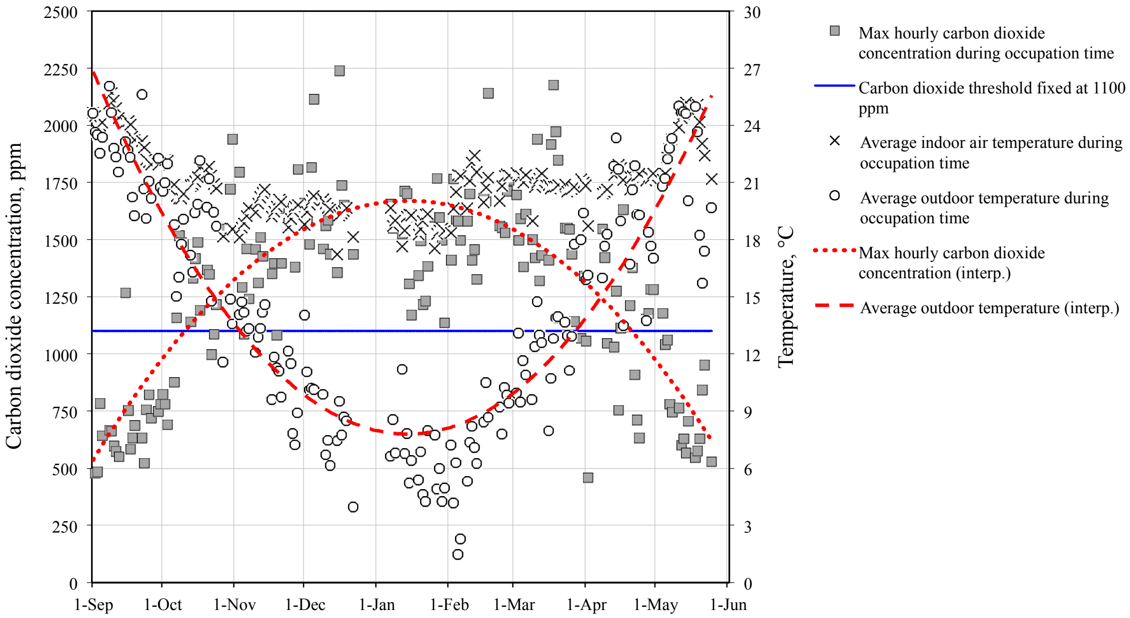

Figure 4: For each day: maximum hourly CO_2 concentration level in Room 4 during occupation hours; indoor and outdoor air temperature values averaged over the occupied hours.

The energy retrofit strategy was, therefore, defined by means of an integrated design process involving the architects of the Municipality of Milan and the authors, which analysed existing constraints and targeted the following goals:

- Reducing the energy need for space heating.
- Reducing all of the energy uses by improving the efficiency of the building's systems.
- Adopting passive strategies for cooling whenever possible, while avoiding the installation of active cooling systems.
- Installing new grid-connected renewable energy generation systems.
- Improving IAQ by installing highly-efficient decentralised ventilation systems, and by implementing an effective ventilation strategy.
- Ensuring adequate thermal comfort conditions all-year long.
- Reducing construction time to limit the disturbance or interruption of the educational service.

Table 1: Description and properties of building envelope components in the pre- and post-retrofit configurations.

Building envelope component	**Pre-retrofit (calculated) U-value, W/(m^{2}K)**	**Post-retrofit (design) U-value, W/(m^{2}K)**
Roof	1.30	0.09
Vertical opaque wall	1.20	0.09
Window (glazing plus frame)	5.80	0.73
Floor (facing an unheated basement)	1.30	0.30

4 Methodology

Building performance simulation is a powerful technique to support not only the design of a new building, or the refurbishment of an existent one, but also in the operation, diagnostics, commissioning and evaluation of the building's performance. In this work, simulation has been used to compare various energy saving measures and refurbishment options in order to guide the definition of the energy concept.

A numerical model of the existing building was created and calibrated against measured delivered energy and indoor air temperatures, then used to define the refurbishment concept of the building, and finally to estimate the performance of the renovated building under typical and future weather scenarios in free-running and conditioned modes.

4.1 Numerical model calibration

Building performance simulation tools are increasingly versatile and are able to implement a considerable number of physical models and several numerical resolution schemes. Their potential for delivering useful forecasts of energy and comfort performances is only tackled through skilled modelling choices and an accurate calibration process. Indeed, the building performance simulation models that are not calibrated or calibrated only based on a single benchmark such as energy use or indoor air temperature, can be significantly unreliable [40].

Calibration is a process where the results of a simulation are compared with measured data to improve the agreement of the simulation outcomes with respect to a chosen set of benchmarks through the adjustment of independent parameters that are implemented in the building model. Though calibration is fundamental, at present there are no internationally-agreed requirements for evaluating the goodness-of-fit of a building energy model, but a few recommendations have been proposed in guidelines, such as the ASHRAE Guideline 14 [41].

The guideline introduces three basic methods to estimate energy use and savings that result from the efficiency measures: the whole building approach, the retrofit isolation approach and the whole building calibrated simulation approach (calibrated simulation). The latter approach considers using simulation programs for the energy modelling of pre- and post-retrofit buildings. The proposed set-up for the calibration by ASHRAE is:

1. Produce a calibrated simulation plan.
2. Collect data from the field.
3. Create a numerical model of the building.
4. Compare simulation model output to measured data.
5. Refine model until an acceptable calibration is achieved.
6. Produce baseline and post-retrofit models.
7. Estimate savings.
8. Report on observations and savings.

The ASHRAE Guideline 14 uses two indices to evaluate the goodness-of-fit of the building energy model: the Mean bias error, *MBE*, and the Coefficient of variation of the Root mean square error, *CV*(*RMSE*).

MBE is a non-dimensional measure of the overall bias error between the measured and simulated data in a known time resolution, and it is usually expressed as a percentage:

$$MBE \equiv \frac{\sum_{i=1}^{N_p}(m_i - s_i)}{\sum_{i=1}^{N_p} m_i} \quad [\%] \tag{1}$$

where m_i (i = 1, 2, …, N_p) are the measured data, s_i (i = 1, 2, …, N_p) are the simulated data at time interval i and N_p is the total number of the data values.

$CV(RMSE)$ represents how well the simulation model describes the variability in the measured data. It is defined as:

$$CV(RMSE) \equiv \frac{1}{\overline{m}}\sqrt{\frac{\sum_{i=1}^{N_p}(m_i - s_i)^2}{N_p}} \quad [\%] \tag{2}$$

where, besides the quantities already introduced in Eq.(1), is the average of the measured data values.

The evaluation of the accuracy of a building energy simulation model is made according to the model's conformity with the recommended criteria for *MBE* and *CV*(*RMSE*). According to the ASHRAE Guideline 14, the simulation model is considered calibrated if it has MBE that is not larger than 5 %, and *CV*(*RMSE*) that is not larger than 15 %, when the monthly data are used for the calibration, and MBE not larger than 10 % and *CV*(*RMSE*) not larger than 30 % when the hourly data are used for the calibration.

In the present work, in order to get a reliable building energy model, and to increase the accuracy of the estimation of the building's performance, the pre-retrofit model of the building underwent two subsequent calibrations. The building model was first calibrated on the basis of the building's measured monthly energy use for heating in conditioned mode, then it was refined in free-running with a second calibration with respect to monitored hourly indoor air temperatures in a selected thermal zone of the building (Room 4). In both calibrations the input weather file for the simulations was constructed by collecting and formatting the data of a weather station in Milano-Bovisa that is in a similar position with respect to the city centre. The weather data were recorded during the same time-interval of the monitored data for the energy use and indoor temperature.

The calibration process requires the identification of those input variables that, at the same time, are affected by uncertainty and can significantly impact on the chosen benchmark. Then, a scale of variation has to be identified for each of them according to the boundary conditions. Table 2 reports the five input variables, the scale of variation and the step size tested in the first calibration.

In order to identify the independent variables that, at the same time, influence the energy and thermal performances of the building and that are mostly affected by uncertainty, we referred to Hopfe [42], who identified through a sensitivity analysis the most influencing variables on both energy performance and thermal discomfort. However, in the present case study of calibration: the room size is fixed and it is not a design variable; the type of windows, the power density of the electric equipment and electric lighting and the number of occupants in the building have been precisely quantified with surveys and an energy audit, and hence they are not sources of significant uncertainty [8]. Therefore, the calibration process focused on testing independent variables that describe infiltration rates, the thickness of the insulating layer of opaque envelope components and, we also added, the global seasonal efficiency of the heating system. As for air infiltration, the ranges of variation of the flow coefficient and flow exponent were set according to the values reported in Table A.1, A.2 and A.3 of Annex A. The thickness of the insulating layer was based on geometric constraints due to the entire thickness of the components, which were measured during the energy audit. Finally, the range of variation of the global seasonal efficiency of the heating system was deduced from calculations based on the Italian standard

UNI TS 11300-2 [43] according to the components that are actually installed in the building. Table 2 presents the independent variables, their range of variation and the step size used in the monthly energy calibration.

Table 2: Input variables for calibration based on monthly values of delivered energy

Source of uncertainty	**Independent variables (unit of measure)**	**Range of variation**
Air-leakage of joints between building envelope components	Flow coefficient ($kg\ s^{-1}m^{-1}crack$ @ 1 Pa)	{Very poor, Poor, Medium}*
	Flow Exponent (non-dimensional)	
Insulation thickness	Wall Insulation (cm)	{1, 2, 3, 4, 5}
	Roof Insulation (cm)	{1, 2, 3, 4, 5}
	Floor Insulation (cm)	{1, 2, 3, 4, 5}
Heating system	Global seasonal efficiency (%)	{45, 49, 53, 57, 61}

* See Annex A for the specific values of Flow coefficient and Flow exponent implemented in the simulations.

According to the calibration problem described in Table 2, a problem space of 1875 building variants was investigated.

The second calibration inherited the model from the first calibration, and it was based on the air temperature monitored in Room 4 (Figure 2) from the 15^{th} May to the 15^{th} July. This period was specifically chosen because the pre-retrofit building was in free-running from the 15^{th} April to the 15^{th} October. Also in the designed post-retrofit model, the building is assumed to be in free-running from the 15^{th} April to the 15^{th} October. Three input variables were chosen. Table 3 shows the independent variables, the range of variation and the steps adopted in the second calibration based on hourly temperatures.

Table 3: Input variables for calibration based on the hourly indoor measured air temperature in Room 4.

Source of uncertainty	Independent variables (unit of measure)	Range of variation
Control strategy of solar shading devices	Indoor air temperature (°C)	{22, 23, 24, 25, 26}
Control strategy of window opening	Indoor air temperature (°C)	{22, 23, 24, 25, 26}
Occupancy	Number of occupants in Room 4 (people)	{20, 25, 30, 35, 40}

The indoor air temperature is used as the control parameter for the control strategies of the solar shading and window opening devices, since in the pre-retrofit situation both adaptation possibilities are manually operated by the teachers on the basis of their personal feelings about the indoor thermal condition. The range of the variations was deduced from the analysis of the monitored data. The number of occupants in Room 4 is affected by a wide day-by-day variability; hence, from a survey of the building staff and from the analysis of the measured CO_2 concentrations, the daily values were deduced and used as the range of variation in the calibration process. According to the calibration problem described in Table 3, a problem space of 125 building variants was investigated.

4.2 Future weather scenarios

The Special report on emission scenarios (SRES) of IPCC working group 3 provides four storylines followed by four scenario families for the future climate, and IPCC working group 1 developed *General Circulation Models* (GCM) as tools for simulating the response of the global climate system to the increase of greenhouse gas concentrations [4]. The combination of GCMs and SRES scenarios are used to predict the future climate. Each storyline considers different future directions. They cover a variety of future characteristics such as social, economical and technological changes. In this paper, we adopted the approach presented by Jentsch et al. [44], who developed a tool called *CCWorldWeatherGen* that provides hourly future weather data that is suitable for building performance simulation. The calculation principles of this tool are based on the A2 emission scenario developed by SRES, the *UK Met Office Hadley Centre Coupled Model version 3* (HadCM3) [45] and a downscaling method called *morphing*, proposed by Belcher et al [7]. HadCM3 is one of the major GCMs that supports the IPCC reports, and the combination of this model with the A2 emission scenario is one of the most widely used combinations in climate predictions [13]. The A2 represents a very heterogeneous world with continuously increasing global population, regional economic development and technological change that is fragmented and slower than in other scenarios. This scenario has a continuous increase in greenhouse gas emission that cause the increase of temperature with best estimate of 3.4 °C at 2090-2099 relative to 1980-1999 [46].

The morphing method allows to downscale the monthly mean predicted data that is created, in this case by HadCM3, to a future hourly weather data, by applying three transforming functions on a 'baseline' hourly weather data file, e.g., a typical meteorological year (having TMY or other equivalent format): shifting, stretching and the combination of shifting and stretching.

Shifting is used when the climate change scenario requires an absolute change to the mean. It has an additive formulation and it adds the HadCM3 predicted absolute monthly mean change (Δx_m) to the TMY hourly data (x_0):

$$x = x \quad + \Delta x \tag{3}$$

Shifting is, for example, used to adjust atmospheric pressure.

Stretching has a multiplicative formulation and scales the TMY hourly data (x_0) by a HadCM3 predicted relative monthly mean change (α_m). α_m is a fractional change between the future monthly values and the existing TMY data according to HadCM3.

$$x = \alpha \quad x \tag{4}$$

Stretching is used, for example, when there is a change to either the mean or the variance. The *combination of shifting and stretching* is a linear combination of the two previous transforming functions:

$$x = x \quad + \Delta x \quad + \alpha \quad x \quad - x \; , \tag{5}$$

The *combination of shifting and stretching* is used when the *morphing* has to be applied to both the mean and the variance of the hourly weather data, for example, in the case of temperature shift, by adding the HadCM3 predicted absolute monthly mean change, it is stretched by the monthly diurnal variation of this parameter. More detailed information is available in Ref.[7].

In our case a typical weather data file from Milano-Linate from the Italian Climatic data collection "Gianni De Giorgio" (IGDG) was downloaded from Ref.[47] and used as a baseline. The above method was applied on this file to obtain hourly weather data for the three future scenarios in the years 2020, 2050 and 2080. For each scenario, the cooling potential of night natural ventilation was evaluated by calculating the number of summer night hours when the outdoor air temperature falls below 20 °C. Moreover, the HDD and CDD values were calculated and compared to evaluate the severity of the different scenarios (Table 4).

Table 4: Comparison of the climate severity of the typical and future weather scenarios and assessment of the cooling potential of night natural ventilation

	Weather scenario			
Parameter (unit of measure)	**IGDG**	**2020**	**2050**	**2080**
$HDD_{20°C}$ (°C h)	3002	2718	2384	1988
$CDD_{26°C}$ (°C h)	3	26	116	289
Night hours when outdoor air temperature is below 20 °C (h)	468	368	266	168

4.3 Set-up of the building energy simulations

The dynamic energy simulation of the building was performed using the software EnergyPlus [48], version 8.3.0.1. Each released version of EnergyPlus undergoes two major types of validation tests [49]: analytical tests, according to ASHRAE Research Projects 865 and 1052, and comparative tests, according to the ANSI/ASHRAE 140 [50] and IEA SHC Task34/Annex43 BESTest method. The building model was set-up with the aim to reproduce the actual geometry of the building in detail, and the algorithms were selected, among the ones available within EnergyPlus, with the aim to represent physical phenomena as accurately as possible, to the expense of computing time.

In detail, the update frequency to calculate sun paths was set to 1 day. The heat conduction through the opaque envelope was calculated via the finite difference method with a 3-minute time step [51]. The natural convection heat exchange coefficient near the external and internal surfaces were calculated via the adaptive convection algorithm [52], to meet the local conditions of each surface of the model. We chose an initialisation period of 25 days, rather than the default value of seven days, to reduce the effect of the thermal initialisation of the model. The voluntary ventilation and involuntary air infiltration were calculated with the *AirflowNetwork* module to better estimate the contribution of natural ventilation due to both infiltration and opening of the windows.

Two sets of simulations were carried out. During the first set, the model was simulated in free-running mode to assess the performance of the building envelope by itself, and passive strategies in the typical (IGDG) and in the future climates. Then, the second set was simulated adding to the model an ideal active system which ensures that indoor operative temperature is maintained at the chosen winter and summer set-point temperatures during occupation hours. According to the Italian law [17], in Milan, the heating season ranges from the 15th October to the 15th April. No indication is provided by legislation on the length and start date of the cooling season. Following the analysis and suggestions in [53], the authors decided to use the period from the 15th May to the 30th September as the 'summer' period, this being the time interval in which the 15-day mean sol-air temperature is higher than the summer set-point temperature. Furthermore, the building was considered unoccupied during all national holidays, weekends, and during August due to the summer vacation, according to the actual schedule.

In the pre-retrofit model used for the monthly energy calibration, the heating set-point for the indoor air temperature was set to 21 ºC according to the data gathered from the building survey.

In the post-retrofit model used in a conditioned mode for the climate resilience assessment, (i) the heating set-point for the indoor air temperature was set to 20 ºC according to the requirement set by the Italian law DPR 412 [17], and (ii) the cooling set-point for the indoor operative temperature was set to 24 ºC, taking as reference the Table A.3 of EN 15251; the rationale for this choice is discussed in the next paragraphs.

There is ample debate and continuous progress on thermal comfort models and their implications on building design, which eventually will translate into a further revision of the standards (both EN and ASHRAE). Among the open issues one might list:

- The Fanger model was derived on the base of a necessary condition of thermal balance and additional conditions, namely two correlations, obtained by observing subjects in thermal comfort. One correlation relates mean skin temperature and activity level, and the second relates evaporative heat loss and metabolic activity. The two correlations were derived by analysing data regarding American college-age subjects in controlled climate chamber (no quantitative correlation index was given) and later compared with similar experiments involving 128 Danish college-age subjects with a mean age of 23 years and 128 elderly subjects with a mean age of 68 years. Specific data regarding small children were not part of the dataset [54]. Therefore, van Hoof [55] underlines that "the PMV model applies to healthy adult people and cannot, without corrections, be applied to children, older adults and the disabled". Some studies that have been published recently deal with comfort the perception and preference by children attending kindergarten or primary school [56–59]. In general, they point to a possible lower acceptance of warm conditions by children compared with adults, but the conclusions are based on various methodological attempts to translate the ASHRAE comfort sensation questionnaire in terms and images accessible to children (hence potentially affected by some semantic distortion) and on corrections to take into account differences in metabolic rate and body area between children and adults. The need for further research is proposed in the cited papers, and none of them reports evaluations on children 3 to 36 months old.

- From statistical analysis of the recognised international thermal comfort survey databases (ASHRAE RP-884 database, SCATs the *Smart Controls And Thermal Comfort database*, BCC *Berkeley City Center project database*), some researchers have suggested that the EN 15251 category I, ranging between PMV values -0.2 and +0.2 (which is called category A in ISO standards), might be too narrow to actually be perceived by subjects [60]. The authors conclude that: "In an analysis of high-quality field studies, the three classes do not exhibit different comfort/acceptability outcomes. The tightly air-temperature-controlled space (class A) does not provide higher acceptability for occupants than non-tightly air-temperature-controlled spaces (class B and C)."
- On the same issue of the operational significance of Category A, Alfano et al. [61] performed an analysis of uncertainty based on error propagation assuming the sensors accuracy required by EN ISO 7726. They conclude that: "the PMV range required by A-category can be practically equal to the error due to the measurements accuracy and/or the estimation of parameters affecting the index itself [62]; as a matter of fact, the errors accepted by EN ISO 7726 in terms of required accuracy give large errors in the PMV value, as in Figure 2". The cited Figure does indeed report uncertainties in the PMV value of the order of 0.8 to 1.1, that is comparable with the widths of the two widest categories: Category II and III defined respectively by the limits -0.5 < PMV < +0.5 and -0.7 < PMV < +0.7.

One consequence of this debate might have been the fact that in EN 15251 the Category I, rather than being implicitly proposed as the one of highest comfort levels as in ISO 7730, has been proposed for "very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons" [63]. However, no statistical analysis is proposed in EN 15251 to support the applicability of Category I to sensitive and fragile people.

While a deeper understanding about comfort categories and child thermal sensations and expectations is being developed, in everyday practice a designer has anyway to choose a reasonable set point during the warm season. A national design value for the cooling set-point is not available in Italy; the value of 24.0 ºC for indoor operative temperature was adopted for this analysis. This value was chosen taking into account the Table A.2 of EN 15251 entitled *Recommended indoor temperatures for energy calculations*, which recommends indoor temperature be in the range 22.5–24.5 °C for kindergartens in Category I, assuming clothing insulation of 0.5 clo and a metabolic rate of 1.4 met correspondent to standing-walking activity.

4.4 Thermal comfort assessment of the post-retrofit building model

A few long-term thermal discomfort indices proposed by the EN 15251 are used to assess the performance of the post-retrofit building model operated in free-running mode. Specifically, the Percentage outside the range method and the Degree hours criterion are suitable to that purpose. The former provides a quantification of the fraction of time during which the indoor operative temperatures exceed the given thresholds that depend on the chosen comfort category. This index is symmetrical, i.e. it measures both overheating and undercooling occurrences. The Degree hours criterion provides a quantification of the magnitude of the overheating phenomenon by summing over the considered period, for each occupation hour, the product of time and the temperature difference of the indoor temperature from the upper temperature limit of the chosen comfort category. This index is asymmetrical, i.e. it measures only the magnitude of overheating occurrences. For a more detailed description of the indices refer to Ref.[35].

In the case where the post-retrofit building model is conditioned, an ideal system provides all of the energy needs required to meet the winter and summer set-point temperatures. The performance of the building in the typical and future climate scenarios is assessed using as a metric the energy need for heating and cooling (that is the energy to be delivered to the conditioned spaces in order to meet the thermal comfort conditions specified in Section 4.3).

5 Results and discussion

First, the results of the calibration of the numerical model are presented to show the reliability of the subsequent analyses. Then, the thermal behaviour of the post-retrofit building model in free-running mode under typical and future weather scenarios is proposed to assess how long the building might be operated in a purely passive way without affecting the thermal comfort conditions of the occupants. These results also highlight the evolution of the building's passive behaviour in future weather scenarios, where, progressively, the summer overheating issue will become dominant. Since the results show that the building cannot rely solely on passive strategies (currently because of space heating, and in the future also because of space cooling), the energy need for heating and cooling the building is calculated assuming that the building is in a fully conditioned mode. These analyses show how the energy need for space heating and cooling will probably vary in future scenarios, implying significant challenges for designers and building managers.

5.1 Calibration of the pre-retrofit building model

The pre-retrofit model was calibrated in order to provide reliable simulation outcomes. Two calibration processes were carried out in order to increase its estimation accuracy. Specifically, the model was first calibrated on the basis of measured monthly delivered energy for heating in a conditioned mode, then the best building variant after the first calibration was refined further by a second calibration, where it was operated in a free-running mode. The benchmark of the second calibration was the hourly indoor air temperature that was measured in Room 4.

The results of the first calibration are: *MBE* and *CV*(*RMSE*) of the monthly delivered energy over the calibration period (year 2014) for the pre-retrofit model are equal to 3.7 % and 11.6 %, respectively, hence the model satisfies the criteria recommended by the ASHRAE Guideline 14 for the monthly data.

Then, the final combination of the best values for the independent variables provided values of *MBE* and *CV*(*RMSE*) equal to 0.8 % and 4.2 %, respectively. Therefore, the model can be considered calibrated according to the ASHRAE Guideline 14. Table 5 reports the values of the independent variables that characterise the calibrated building variant.

Table 5: Values of the independent variables that characterize the calibrated building variant

Source	Independent variables (unit of measure)	Scale of variation	Best value
Air-leakage of joints between building envelope components	Flow coefficient (kg $s^{-1}m^{-1}$crack @ 1 Pa)	{Very poor, Poor, Medium}	Poor
	Flow Exponent (non-dimensional)		
Insulation thickness	Wall Insulation (cm)	{1, 2, 3, 4, 5}	2
	Roof Insulation (cm)	{1, 2, 3, 4, 5}	2
	Floor Insulation (cm)	{1, 2, 3, 4, 5}	3
Heating system	Global seasonal efficiency (%)	{45, 49, 53, 57, 61}	53
Control strategy of solar shading devices	Indoor air temperature (°C)	{22, 23, 24, 25, 26}	24
Control strategy of window opening	Indoor air temperature (°C)	{22, 23, 24, 25, 26}	25
Occupancy	Number of occupants in Room 4 (people)	{20, 25, 30, 35, 40}	25

Figure 5 depicts the comparison between the simulated and the measured indoor air temperature in Room 4. The calibrated model of the pre-retrofit building reproduces the general thermal behaviour of the actual building with a good agreement, and it catches the main peaks. It is characterised by slightly wider fluctuations and a more rapid variation of the indoor air temperature as a consequence of sudden changes in the outdoor air temperature than the actual building. This can partly be explained by the lower thermal inertia considered in the model compared to reality, since furniture and equipment were not modelled. After the second calibration, the refined model is used as a baseline to support the design of the retrofit and create the post-retrofit building model.

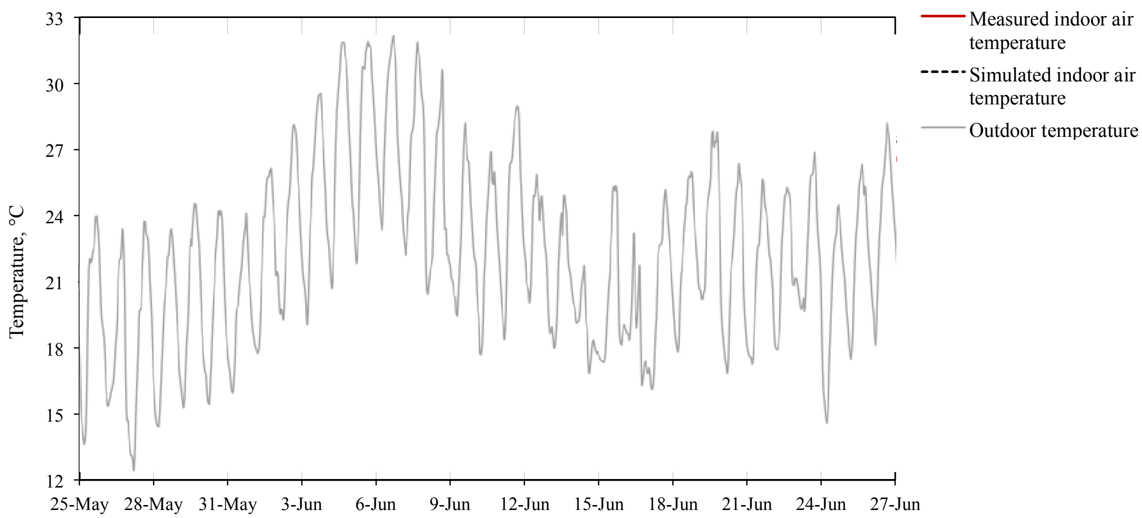

Figure 5: Comparison of the simulated and monitored indoor air temperatures in Room 4. The shaded area represents a measurement uncertainty of ±0.5 ℃.

5.2 Performance of the post-retrofit building model under current and future weather scenarios

After calibrating the pre-retrofit model, the post-retrofit model of the building was built and simulated under typical (IGDG) and future weather scenarios. The performance of the post-retrofit building was evaluated by first assuming that the building is operated in free-running mode by evaluating the long-term thermal discomfort indices that are proposed by EN 12521 (the *Percentage outside the range method* and the *Degree hours criterion*), then in conditioned mode by calculating the energy needs for heating and cooling.

5.2.1 Post-retrofit model simulated in free-running mode

The building has been simulated in free-running mode, i.e. keeping both the heating and the cooling systems off for the whole year. The internal gains, i.e. the heat produced by the occupants and the internal electrical loads for lighting and appliances, are taken into account in the simulations. The obtained results provide information on the periods in which the building might potentially work in free-running mode, and the frequency and intensity of overheating throughout the whole year.

Figure 6 shows, only for the hours when the school is occupied, the indoor operative temperatures in the building (averaged over all of the occupied zones) obtained by simulation using the IGDG weather file and the weather projections for 2020, 2050 and 2080, which were plotted against the running mean of the external temperature[5] over the entire year. The hourly indoor operative temperatures are compared to the EN 15251 comfort thresholds for Categories I, II and III for the warm period of the year.

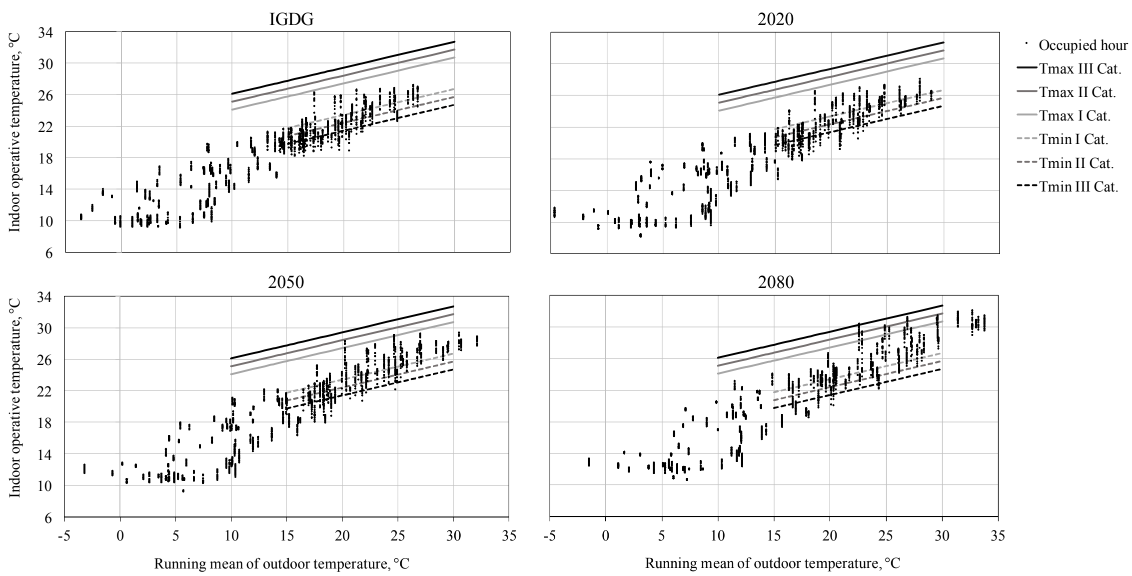

Figure 6: Indoor hourly operative temperature versus the running mean of daily outdoor temperature with the building operated in free-running mode, under typical (IGDG) and future weather scenarios (2020, 2050, 2080).

As discussed in the previous parts of this paper, the child care centre is occupied by children who are 3 to 36 months old and the information on thermal comfort for this age range is scarce and it has not yet been

[5] The *running mean of the external temperature* is defined in EN 15251 as the "exponentially weighted running mean of the daily mean external air temperature" [14].

incorporated into thermal comfort models. Hence the data obtained for the simulations over the IGDG and future weather scenarios are not only compared to Category I suggested in EN 15251 for "very sensitive and fragile persons" [14], but also to the other two categories.

According to the simulations, the energy concept developed for the retrofit of the building works quite well with respect to overheating during the summertime in the typical weather file (IGDG) scenario and under a near future scenario (2020); whereas the indoor temperature is outside the upper thresholds of the comfort categories in the 2050 and 2080 scenarios, but only for a few hours. However, when considering both the upper and lower thresholds, the amount of hours when the indoor operative temperature is outside the adaptive comfort categories is quite large. In order to quantify this behaviour, Figure 7 shows the percentage of hours when the running mean of the outdoor temperature falls inside or outside of the range of the running mean of the outdoor temperature where the EN adaptive comfort model is applicable. Three regions are identified in this way: a heating region where the running mean of the outdoor temperature is lower than 15 °C, an adaptive region where it is between 15 and 30 °C, and a cooling region where it is higher than 30 °C.

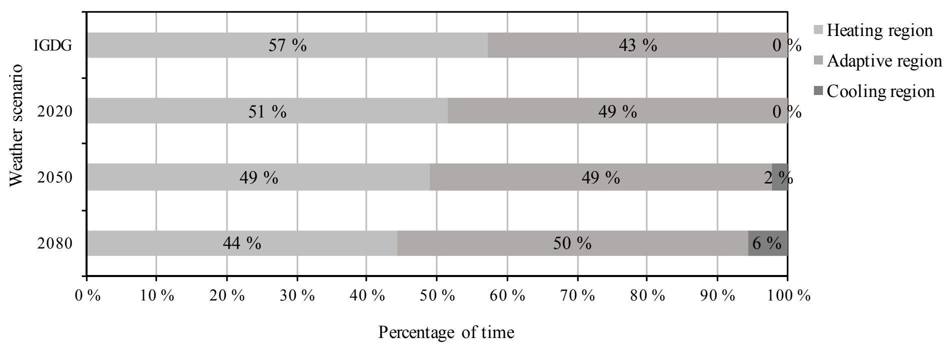

Figure 7: Percentage of time over the entire year when the running mean of the outdoor temperature falls into the region where the European adaptive comfort can be used, into the active heating region and into the active cooling region

The simulations under the future scenarios show a significantly important reduction in the hours when active heating is required (44 % of time in 2080 compared to 57 % in IGDG scenario), and an interesting expansion of the period when the EN adaptive comfort model can by applied (50 % in the 2080 scenario versus 43 % in the IGDG scenario). Finally, the 2050 and 2080 scenarios show that in 2 % and 6 % of the occupied hours, respectively, the running mean of the outdoor temperature falls outside of the domain of the adaptive model on the upper side. During this time the EN adaptive comfort model cannot be used any more, and an active cooling system should be used to ensure thermal comfort conditions. Therefore, PMV has to be used again, according to EN 15211, with a consequent problem in the discontinuity of design implications and temperature set-points, as already discussed in Ref.[64].

Free-running indoor conditions change considerably in future climates, as shown in the cumulative distribution of the indoor operative temperatures that are presented in Figure 8.

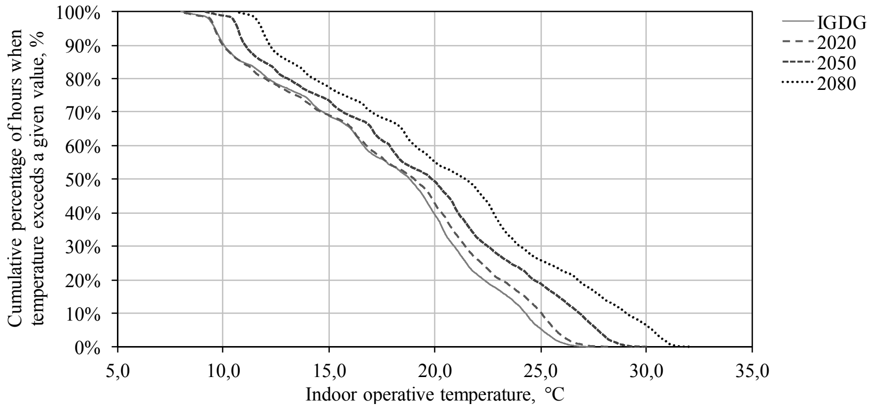

Figure 8: Cumulative representation of hourly values of indoor operative temperature (averaged over all occupied zones) of the entire year, for post retrofit model in free-running mode in the four weather scenarios.

Focusing on the summer period, defined here as ranging from the 15th May to the 30th September, Figure 9 shows the outcome of the Percentage Outside of the Range Method, which quantifies to what extent the average indoor operative temperature falls with respect to the EN 15251's comfort categories during occupied hours.

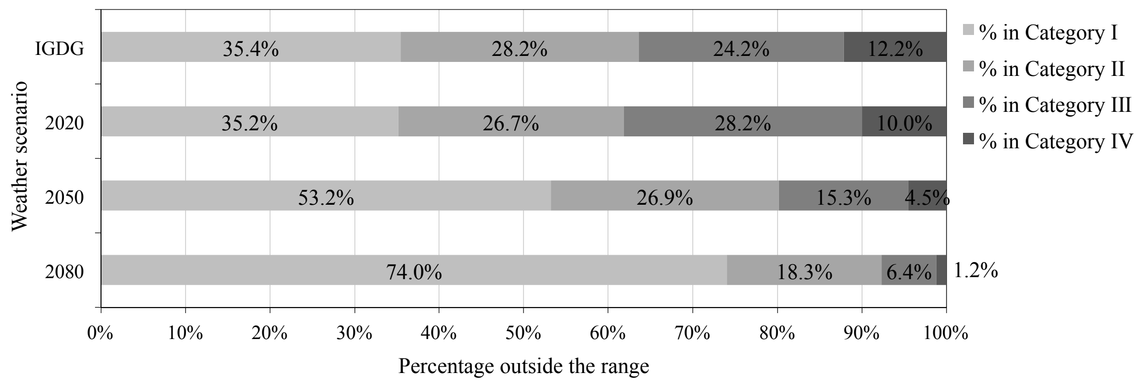

Figure 9: Thermal comfort footprint representing the percentage of occupied hours indoor when the average operative temperature is within the boundaries of the comfort categories proposed by EN 15251 under the IGDG and the future weather scenarios for the post-retrofit building model in free-running mode in the period from 15th May to 30th September.

It might appear surprising that the percentage of the occupied hours when the indoor operative temperature falls inside Category I significantly increases (from 35 % to 74 %) in the future weather scenarios. However, since the Percentage Outside of the Range Method is a symmetric long-term thermal discomfort index, it records both the occurrences due to overheating and those due to undercooling. In order to better understand the source of thermal discomfort, the frequency of overheating and undercooling referring to all of the three comfort categories are represented separately in Figure 10.

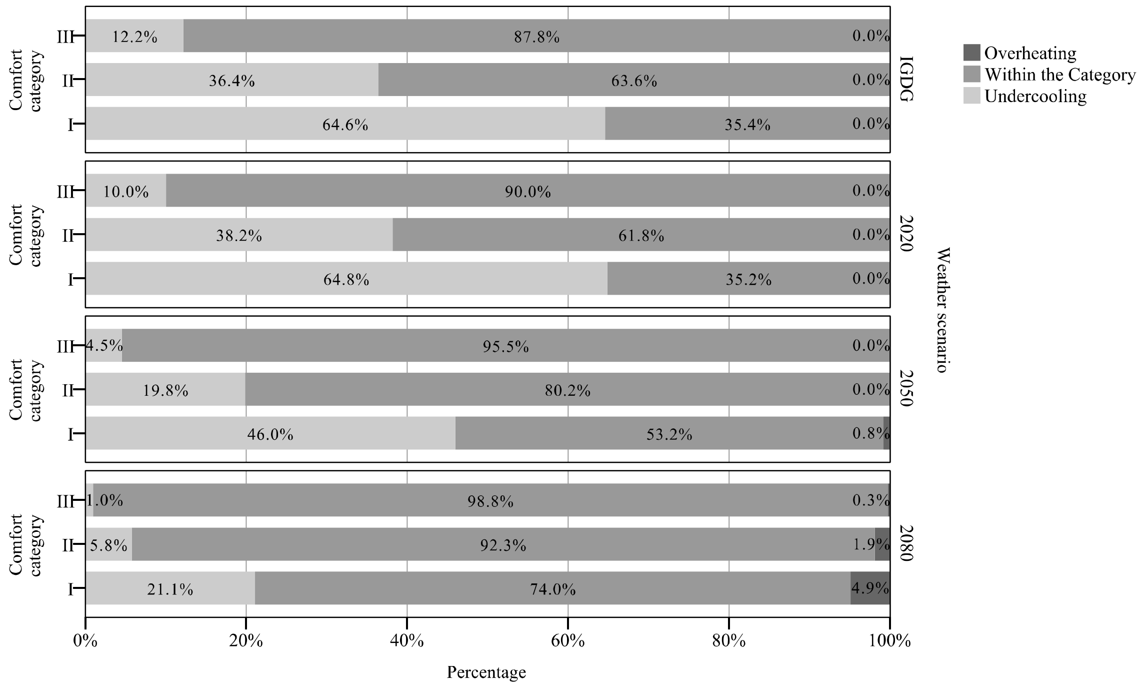

Figure 10: Percentage of hours with overheating or undercooling occurrences referred to the adaptive comfort categories I, II and III under IGDG and future weather scenarios for the post-retrofitted building model in free-running mode.

Limited to the climate of Milan, during the summertime and with the post-retrofit building being operated in free-running mode, when the indoor operative temperature falls outside of a given comfort category, in most of the cases, the cause of the thermal discomfort is due to undercooling, defined as the condition when the indoor operative temperature is below the lower limit of a given comfort category. Only in the 2050 and 2080 scenarios, and with respect to Category I and II, the occurrence of indoor operative temperatures that are above the upper limit of those comfort categories are found as the source of thermal discomfort for a maximum of 5 % of the occupied hours. If a designer were to try to optimise the building using this index under the IGDG scenario, he/she might be brought to select, for example, a configuration of the envelope with a lower performance than considered here (in order to shift all of the indoor temperatures during the summer upwards, under the IGDG scenario). This would have the drawback of increasing the risk and occurrence of overheating when the weather evolves to a warmer configuration in the future, as noticed in [64]. Symmetry of comfort category is reported in both EN 15251 and ASHRAE 55, but it seems to be more of a result of assumptions [65], than the outcome of statistical analyses. Indeed, a certain deviation from symmetry in thermal preferences was already found by Nicol and Humphreys [66]. Furthermore, one might argue that overcooling might be easier to manage than overheating, via adaptations in clothing in the first hours of the morning, and, in this particular building, by adopting a finer control of the night cooling ventilation.

Figure 11 shows the intensity of the deviation quantified by the degree hours criterion proposed by EN 15251. It is an asymmetrical index, since it cumulates only degree hours of exceedance above the upper threshold of a given comfort category (during the summer) or it cumulates only the degree hours of exceedance below the lower limit of a given comfort category (during the winter).

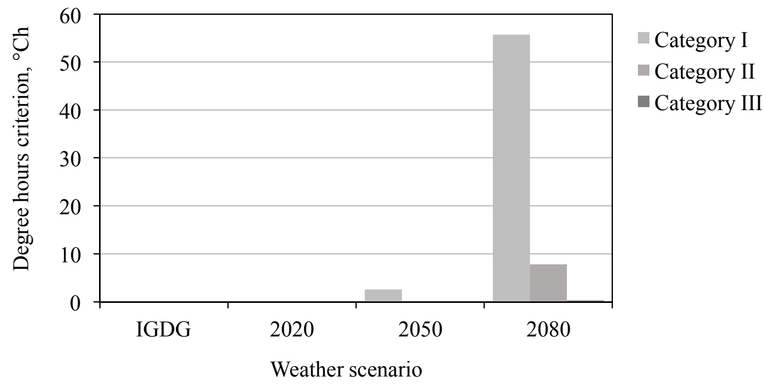

Figure 11: Degree hours criterion for summer (only overheating occurrences are counted) for the three adaptive comfort categories in the four simulated scenarios.

According to the simulations and the assumed morphing transformation of the weather, the post-retrofit building model performs considerably well in the summer conditions, and, even in 2080, the overheating issues appear to be limited with only a few occurrences in July. However, it should be considered that the thermal discomfort is assessed using the adaptive comfort model, thus the lower and upper temperature thresholds vary according to the running mean of the outdoor temperature, which is rising in future weather scenarios, i.e. 2020, 2050 and 2080. However, the improvements of the thermal comfort models are outside of the scope of this paper. As for the long-term indexes, our analysis suggests that care should be taken in using the symmetric indexes, since focusing on overcooling in the present weather might make the building less resilient to overheating in the future climate conditions. This reinforces the need to verify if the assumption of symmetry of the thermal comfort categories with respect to the optimal comfort temperature is reliable, or if amendments might be required on this point.

Even with a high-performance envelope and well-designed passive techniques, the introduction of an active cooling system (either vapour compression, solar assisted absorption, evaporative or combinations) might become necessary as the climate gets warmer and there are fewer opportunities for free-cooling with natural ventilation [67]. However, the simulations lead to conclude that the post-retrofit building model will be able to run in purely free-running mode during the summer (given the uncertainty related to the prediction of future weather conditions) for the next 30 years approximately, while it could operate in a mixed-mode after the installation of a cooling system, i.e. exploiting the remaining free-cooling potential and relying on the active system for critical conditions.

Ideally, the design of a new building or a retrofit should be conducted with this long-term vision, including, from the start, passive physical features that are able to make the building's fabric resilient to future weather and a plan for installing a cooling system when it eventually becomes necessary. For example, in the case of new constructions, one might foresee and allow for the technical spaces required for the later installation of radiant technologies and a mechanical ventilation system. However, one should also consider that, in the next 30 years, cooling technologies might evolve significantly, making it hard to determine now which systems (for generation, distribution and diffusion) would be an optimal choice in the future.

5.2.2 Post-retrofit model simulated in a conditioned mode

The second set of simulations considers the building operated in a conditioned mode for both the winter and the summer periods assuming that the required energy is provided by an ideal system. Therefore, the second set of simulations allows for the estimation of the energy need for heating and cooling required by the building to maintain the set-point temperatures mentioned in Section 4.3 throughout the year.

Figure 12 shows the yearly heating and cooling energy need for space heating and cooling throughout the whole building under the four climatic scenarios under study.

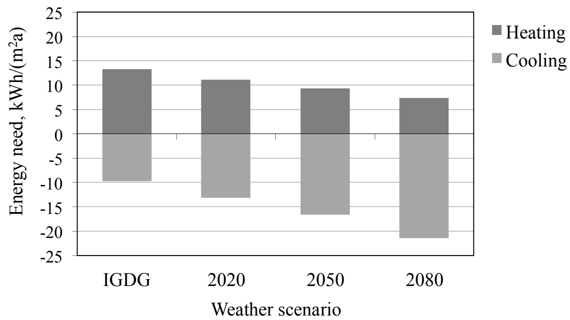

Figure 12: Yearly energy need for space heating and cooling per unit of net floor area.

When the climate evolves to a warmer configuration, the energy need for space heating is reduced, whereas the energy need for space cooling increases. Table 6 reports the yearly energy need for heating and cooling under the future weather scenarios, and their percentage variations calculated with respect to the situation corresponding to IGDG.

Table 6: Yearly energy need for space heating and cooling for the post-retrofit building model under future weather scenario and percentage variations with respect to IGDG.

	Weather scenario			
Parameter, unit of measure	**IGDG**	**2020**	**2050**	**2080**
	Heating			
Energy need, (kWh $m^{-2}a^{-1}$)	13.4	11.2	9.4	7.5
Variation with respect to IGDG (%)	-	-16 %	-30 %	-45 %
	Cooling			
Energy need, (kWh $m^{-2}a^{-1}$)	9.7	13.3	16.8	21.6
Variation with respect to IGDG (%)		+37 %	+73 %	+123 %
	Heating and cooling			
Energy need, (kWh $m^{-2}a^{-1}$)	23.1	24.5	26.2	29.1
Variation with respect to IGDG (%)	-	+6 %	+13 %	+25 %

Figure 12 and Table 6 show that the total energy need of the building will shift towards space cooling as the climate gets warmer. Also the national energy demand might shift from natural gas (which is typically used for heating in Italy) to electric energy, to an extent dependent on which fraction of active cooling will be realised via compression cooling. Moreover, the whole energy need for space conditioning (heating plus cooling) will increase up to 25 % in 2080 with respect to the IGDG scenario, and it will take an even higher impact if it is considered in terms of primary energy. Therefore, it is of national interest to manage the actual primary energy demand of the building sector in the coming years, which will be influenced more and more by the evolution and the penetration of renewable generation technologies, as well as by the efficiency of the electric grid.

6 Conclusions

An energy retrofit project for a child care centre targeting very high energy and indoor environment performances has been developed on the basis of a typical (IGDG) weather file. IGDG and TMY weather files were built using data from the climate conditions of past decades. The building model has been simulated taking into consideration the future weather scenarios developed according to the *morphing* methodology applied to the IGDG file. The objective of the analysis was to investigate whether the chosen energy concept would be resilient to the expected future climate changes.

The analysis showed that the design approach based on the substantial exploitation of passive strategies and the improvement of envelope thermal resistance and solar protections may result quite robust in the mid-term weather scenario, justifying the initial capital investment. In the long-term weather scenario, however, in order to be able to cope with the warmer outdoor conditions, the building will probably have to integrate an active cooling system (compression, absorption, evaporative etc.), hopefully optimised to operate in a mixed-mode with natural ventilation.

As for the use of the long-term thermal discomfort indexes, our analysis suggests that symmetric indexes should be used with caution, since focusing on overcooling in present weather might make the building less resilient to overheating in the future climate conditions. Rather, the physical features allowing the building to manage the summer loads should be installed and their exploitation graduated through controls to follow the evolution of the climate. There might also be scope for further analysis on whether the long-term thermal discomfort indexes should consider comfort categories that are strictly symmetrical with respect to the optimal comfort temperature.

In general, the analysis showed that in future weather conditions a substantial shift from heating energy needs to cooling energy needs would be registered in building operations in a temperate climate such as Milan, Italy, which is a winter dominated climate nowadays. A higher shift might be expected at lower latitudes, and should be considered by designers.

A design shift from ‘static’ buildings into buildings that can respond and adapt to climate change is therefore required. Moreover, it should also be considered that the applicability of the available comfort models nowadays to child care centres and kindergartens presents several limitations. The Fanger model was developed in climate chambers through interviews with young adults. The adaptive model is suggested by EN15251 “for human occupancy with mainly sedentary activities and dwelling, where there is easy access to operable windows and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions” [14], but young children do not have the same opportunities as adults regarding behavioural adjustment, physiological acclimatisation and psychological habituation, as classified by Brager and de Dear [68], to adapt to the thermal environment. For example, they do not have direct control over operable windows, and cannot easily adjust their clothing or get themselves hot and cold food and drinks. In addition, they present a higher metabolic level when compared to sedentary adults, given both by physiological aspects and by activities/games performed at the care centre. Thus, the most important adaptive measures are due to their teachers, who need to take decisions for the whole classroom, e.g., the operation of windows and the scheduling of activities.

Considering this, the reported results might be slightly optimistic and the need for an active cooling system could be required earlier in buildings that are occupied by children, compared to offices or other kinds of buildings. Meanwhile, there is probably a need to improve the adaptive and the thermal comfort models in general, and the long-term thermal discomfort indexes, in order to provide the designers with better analysis tools to address climate change in buildings design.

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9 Annex A – Crack templates

Table of data with flow coefficient, *C*, and flow exponent, *n*, are presented for the following components: windows, doors, walls, roof and floor.

The crack characteristics of windows and doors are normalised by opening perimeter lengths. Porosity of walls, roof and floor has been modelled as a single equivalent crack for each component.

Table A.1: Predefined crack template values - Very poor

Component	Flow coefficient (kg $s^{-1}m^{-1}$crack @ 1 Pa)	Flow Exponent (non-dimensional)
Internal windows	0.0030	0.60
External windows	0.0030	0.60
Internal doors	0.0030	0.60
External doors	0.0030	0.66
Internal walls	0.0190	0.75
External walls	0.0004	0.70
Roof	0.0030	0.70
Floor	0.0002	0.70

Table A.2: Predefined crack template values - Poor

Component	Flow coefficient (kg $s^{-1}m^{-1}$crack @ 1 Pa)	Flow Exponent (non-dimensional)
Internal windows	0.00180	0.60
External windows	0.00100	0.60
Internal doors	0.02000	0.60
External doors	0.00180	0.66
Internal walls	0.00500	0.75
External walls	0.00020	0.70
Roof	0.00015	0.70
Floor	0.00020	0.70

Table A.3: Predefined crack template values - Medium

Component	**Flow coefficient (kg $s^{-1}m^{-1}$crack @ 1 Pa)**	**Flow Exponent (non-dimensional)**
Internal windows	0.00014	0.65
External windows	0.00140	0.65
Internal doors	0.02000	0.60
External doors	0.00140	0.65
Internal walls	0.00300	0.75
External walls	0.00010	0.70
Roof	0.00010	0.70
Floor	0.00090	0.70