COMFORT AT THE EXTREMES

INVESTING IN WELL-BEING IN A CHALLENGING FUTURE

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Evaluating User Adaptation and Building Retrofit Strategies to Address Overheating in a Climate Change Scenario: A Focus on Energy Poverty and Vulnerable Users

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Abstract

In the European Union, approximately 50 million households suffer from energy poverty, placing vulnerable groups—such as the elderly, children, pregnant women, the infirm, and people with disabilities—at increased risk of overheating, especially under climate change scenarios. This study investigates the effectiveness in the long-term of passive overheating mitigation strategies for residential buildings, focusing on those occupied by elderly individuals and children up to fifteen years old.
Using a typical 1960s residential building in Milan as a case study, dynamic building energy simulations were employed to evaluate various passive cooling techniques, including natural ventilation and ceiling fans. These strategies were analyzed both pre- and post-retrofit, with the retrofit primarily enhancing building insulation. The results demonstrate that while these passive methods can lower indoor temperatures effectively, they may not suffice to maintain comfort levels in the future, suggesting the need for active cooling systems in retrofitted buildings.
The study further includes a comparative analysis between baseline and retrofit scenarios, assessing the energy consumption, economic impact, and environmental benefits of the proposed strategies. The findings reveal significant improvements in energy efficiency and cost savings, alongside notable environmental advantages with the use of natural ventilation combined with fans.
Additionally, this research emphasizes the importance of incorporating the resilience and adaptability of occupants through phased renovation strategies. By combining lean and deep renovation approaches, this comprehensive framework aims to tackle the challenges posed by climate change, ensuring long-term sustainability and comfort in residential buildings for energy-poor communities.
As a practical outcome, the study proposes a user guide to help residents achieve thermal comfort through effective use of passive and active cooling strategies, ensuring their homes remain livable and energy-efficient in the face of evolving climate conditions.

Keywords

Building engineering, building resilience, passive design strategies, heat stress and thermal comfort.

Introduction

In recent years, climate change has been escalating as a global issue and its effects become more evident each year. These effects include rising temperatures, glacier melting, desertification, and extreme weather events such as tsunamis and floods. Since the 1800s, human activities, particularly since the Industrial Revolution, have been the primary drivers of these changes, releasing pollutants into the atmosphere and intensifying the natural greenhouse effect, resulting in numerous adverse impacts.
To address this urgent issue, several global agreements and frameworks have been established, including the UN Framework Convention on Climate Change [1], the 2030 Agenda [2], the Paris Agreement [3] and the European Green Deal [4]. These documents aim to set targets to limit climate change by considering emissions comprehensively. Additionally, specific guidelines have been developed for sectors with significant impacts, such as the construction sector, which accounts for 42% of energy consumption and 36% of energy-related greenhouse gas emissions worldwide [5] [4].

Key directives for the building sector include the Energy Efficiency Directive [6] and the Energy Performance of Building Directive [7]. These directives set long-term limits to reduce the sector's CO_2 emissions by promoting construction strategies that create energy-efficient buildings while ensuring excellent user comfort.

Besides climate change, energy poverty is another major problem, affecting over 50 million households in the European Union alone [8]. Energy poverty refers to the inability to access essential energy services, compromising living conditions and health, particularly for vulnerable people such as pregnant women, the infirm, people with disabilities, children, and the elderly [9].

Given these challenges, prompt interventions are necessary to find lean and affordable solutions.

The aim of this research is therefore the identification of those passive strategies used to date that can be significantly effective in limiting the problem of overheating, not only by verifying their effectiveness in the current scenario, but also in the future, considering climate changes.

This study focuses on the comfort needs of fragile users because of their particular sensitivity to thermal discomfort and extreme heat events.

To evaluate the effectiveness of these strategies, the research involves analyzing current thermal comfort standards and comparing them with the specific needs of these vulnerable groups. Additionally, the study requires software capable of generating future climate data.

The goal of the study is to provide practical solutions that can be implemented widely, under a strict timeline and to mitigate the adverse effects of rising temperatures and ensure better living conditions for those most affected.

Research methods

Reference standard assessment

The effects of heat on human health are manifold and can go as far as to have serious consequences, particularly for fragile categories. This study focuses on the elderly and young children up to 15 years old. To identify the most suitable standard for assessing user comfort, an analysis of the primary thermal comfort standards is conducted. This analysis serves as a guideline for the subsequent comfort evaluation. ASHRAE 55 [10], ISO 7730 [11], ISO 7933 [12], ISO 7423 [13], UK Document O [14], ISO 17772 [15] and ISO 16798-1:2019 [16], were analyzed but only the last two were selected because of their specific focus on the user categories objective of the study.

- ISO 17772: Define comfort Category I suited for fragile users and provides specific guidelines for optimizing the energy performance of building systems while ensuring indoor environmental quality (IEQ).
- ISO 16798-1:2019: is broader and is primarily concerned with setting design parameters and evaluating existing building's performance and is valid for residential buildings where people are performing mostly sedentary activity. It also defines Category I of comfort for elderly and young children.

Comfort temperature threshold selection

The elderly, due to the age effect, react more slowly to an environment perceived as "too hot" [17] and so it is necessary that the environments the user is exposed to, are constantly controlled. From a medical point of view, a temperature between 23°C and 28°C in summer can be suitable for the elderly. The risk for heat stroke increases when the temperature starts to rise and the situation begins to be risky for their health when the temperature reaches 30°C. Under these circumstances, an exposure equal to or higher than 6 hours to this or higher temperatures can be dangerous for their health [18].

On the contrary, for users in the 0-15 age group, thermal comfort conditions change considerably due to the rapid changes that a human being undergoes in this age group.

The children's group was then divided into two subgroups: one considering the children from 3 to 15 years old and the other considering the infants from 0 to 2 years old.

For the first sub-group the comfort limits normally used for adults should be lowered due to the different metabolism and the major capability to adapt to different thermal environments of children [19] [20] [21] [22]. Delving into the specifics, for children aged 3 to 10 years, the reduction in temperature, considering the limits of comfort category I of ISO 16798-1, is 1.9°C [23]. For those aged 11 to 15 years, the reduction, again considering the limits of comfort category I of ISO 16798-1, is 0.8°C [22]. In both age groups, however, the maximum temperature to which they can be exposed for more than 6 hours is 30°C.

For children from 0 to 2 years old, the adaptive comfort limits of category I in ISO 16798-1 are generally valid, as the standard deems these limits suitable for very young children [24]. The only modification is related to the maximum allowable temperature, which is 26°C [25], thereby excluding a significant portion of comfort category I.
Because of the more conservative assessment, ISO 16798-1 was used in this study.
Given that the standard is valid for naturally ventilated buildings where occupants are engaged in sedentary activities and the limits of category I, with minor variations, apply to all age groups, it was decided to consider this standard in the research adding the two static limits, 26°C and 30°C, mentioned before. This approach highlights the maximum temperatures that can be tolerated by users.
In the graphs showing the results of the various thermal simulations, both limits will therefore be shown to understand not only whether the environment studied is comfortable, but above all whether it is more suitable for one category than another.

Future climate generation

Currently, there are several programs that enable the simulation of long-term climate scenarios and five of them have been analyzed to find the most suitable one. These are: Meteonorm [26], Weather Morph [27], Weather Shift [27], CCWorldWeatherGenerator [27] and Future Weather Generator (FWG) [27].
Although Meteonorm was initially considered, a scientifically validated, non-commercial alternative that better aligned with the project's focus, was proritized. As a result, Meteonorm was excluded from further analysis.
Turning to Weather Morph software, it was possible to see that the software does not take extreme events into account when generating future climate data, but only average conditions. Furthermore, the spatial grid on which the software is based has a low resolution, not leading to an accurate forecast as it is based on an average of the four nearest locations.
Using CCWorldWeatherGenerator, it became evident that it only accounts for the A2 future emission scenario and, similarly, does not consider extreme events when generating future climate data, focusing solely on average conditions.
Lastly, considering FWG, simulations of future weather for the city of Milan were also carried out, but this time it was possible to see how they agreed with the hypothesis that sees an increase in the direct component at the expense of the diffuse one. Furthermore, there are many advantages to this software, including the fact that it has a global fine area resolution, it uses a bilinear interpolation of the four nearest points in case the location of the project does not correspond to a grid point and it considers both typical and extreme weeks of each season in the generation of future climate data [27] .
For these reasons, it was decided to use this latter software to generate the future climate data that will be used in the analyses in the following chapters.
The software generates data for four scenarios—SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5—across two future periods: 2050 and 2080. For these analysis, scenario 4.5 was selected for 2050 and scenario 8.5 for 2080, representing an intermediate and a worst-case scenario, respectively. Results for both future scenarios, as well as the present-day scenario, will be included in the charts for comparison.

The energy model

The study focuses on a residential social housing building built between 1962 and 1965 in Milan, latitude and longitude coordinates are 45.46, 9.18 and the climate is classified as Cfa considering the Koppen classification.
The building has ten floors with three central stairwells giving access to two flats each per floor, for a total of 60 flats. The building is oriented so that the flats face south-east and north-west.
The building was modelled under dynamic thermal conditions through IES-VE 2023 [28], to perform long-term evaluations of the most common passive strategies used in buildings today and develop an assessment of the strategies' effectiveness under future conditions.
The baseline configuration is a non-insulated building made with prefabricated modular components. The thermal transmittance value of the external walls is 2,87 W/m^2K, including thermal bridges, and the windows are all single-glazed with a correspondent thermal transmittance value of 5,69 W/m^2K for glass-only. No shadings systems are present.
A conservative approach was used for the selection of internal gains profiles, the presence of people equal to 100% during night hours and the use of electrical appliances equal to 50% during night hours are taken

into account. In contrast, natural ventilation and the presence of heating or cooling systems are not implemented.
This building configuration is considered as the starting point of the analysis that will be presented in the following paragraph, to test different strategies, mainly passive, to guarantee the thermal comfort of the users in the present and possible future scenarios.

Workflow for renovation and passive strategies assessment
Starting from the baseline configuration just presented, it was decided to insulate the building by modifying the baseline stratigraphy of the external wall, adding an external layer of 15cm of rockwool with a conductivity of 0,047W/mK.
Thanks to this layer the new value for the thermal transmittance of the external walls is equal to 0,24 W/m^2K.
Another change that has been made to the envelope is the type of window. The type was changed from single-glazed to double-glazed, obtaining a new value for the thermal transmittance of the glass equal to 1,39 W/m^2K. Due to this change the g-value of the glass changed from 0,82 to 0,60.
Two different types of shading systems were already tested: shutters and fixed horizontal lamellas.
Shutter was considered because it is one of the most common systems, often already present in buildings and its cost is limited. Due to its shape, this system has a very low transmission factor of the incident solar radiation.
Fixed horizontal lamellas were considered because, since they have a different shape with respect to the roller shutters, they allow a different transmission of the solar radiation inside the building. These lamellas are considered fixed in that their inclination cannot be changed, but they can be moved in a vertical direction and thus be compacted in the upper part of the window and not considered active during the months when they are not needed. The size of the lamellas is 190X34mm and their spacing is 190mm.
Different activation profiles of the shading systems were implemented in the model assuming that shading systems are active in the morning for the SE room and in the afternoon for the NW room. In both cases, the percentage of activation of the systems is directly proportional to the incident global radiation.
In the SE room, these activate when the global horizontal irradiance (igh) is equal to 300 W/m^2 and are completely active when the igh is equal to 900 W/m^2, in the NW room these activate when the igh is equal to 100 W/m^2 and are completely active when the igh is equal to 1100 W/m^2. The threshold of activation was defined in accordance with a preliminary sensitivity analysis.
Different profiles for natural ventilation were then implemented, initially considering only single-side natural ventilation. This method was adapted according to the month and scenario considered.
During the hottest months of the year, May to August, cross-ventilation had to be implemented in the model. This was possible by incorporating a series of open doors and windows in two additional rooms to ensure effective cross-ventilation during extreme heat conditions. During those months of the year when natural ventilation was not active, an air exchange of 0.15ach was guaranteed.
In both ventilation cases, it is important to emphasize the significant reduction in air changes per hour (ACH) during periods when the shading systems are in use. When the shutters are active, the ACH is estimated to decrease by 90%, whereas when the lamellas are active, the reduction is only about 10%.
Given the large number of flats, an initial analysis was conducted using IES-VE to identify the coldest and warmest flats, as these represent the most thermally unfavorable conditions. The results of this first analysis are reported in the chart on the left (fig. 1a), while the two most unfavourable flats are highlighted in the schema on the right (fig. 1b).

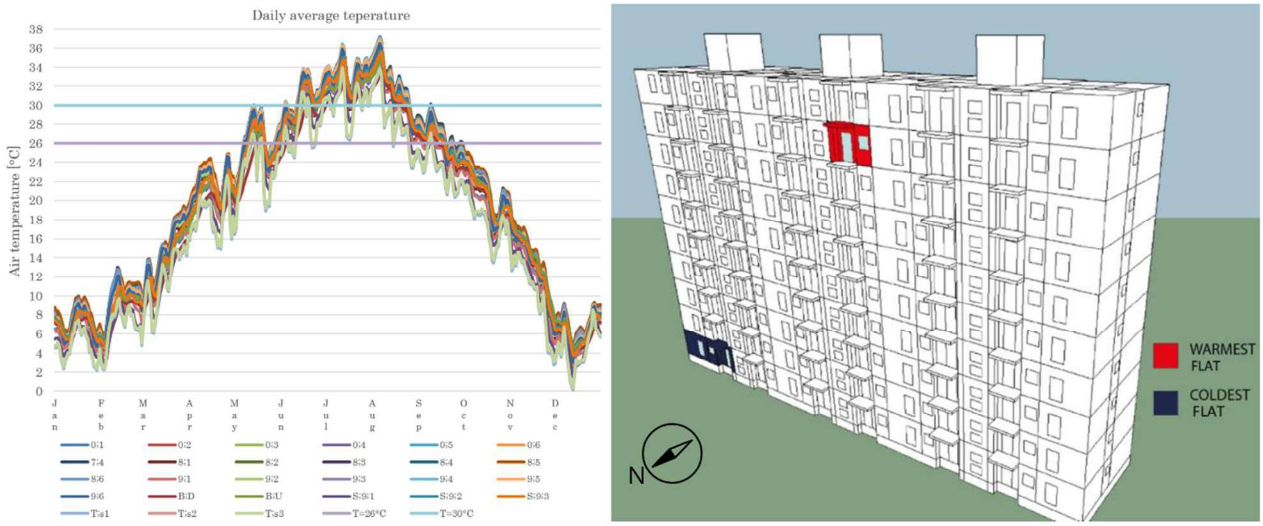

Figure 1a and 1b: First analysis of the building

On the left, the daily average temperatures of selected apartments. The first number indicates the floor and the second the apartment. On the right, 3D view of the building with the coldest and the hottest apartments highlighted.

Following the initial analysis, a second assessment was conducted to identify the two most critical rooms, specifically bedrooms and living rooms, as suggested by the CIBSE TM59 standard, in the two previously identified critical apartments [29].

In the case of the coldest flat, room 0,1-1 turns out to be the coldest room in the coldest flat (under winter conditions). In the case of the hottest flat, room 8,4-3 turns out to be the hottest room in the hottest flat (under summer conditions).

For simplicity, due to their orientation, the coldest room will be the NW room and the hottest room will be the SE room.

Going forward, the analysis will focus exclusively on these two rooms, both of which are bedrooms. Consequently, the evaluation will concentrate on the nighttime hours specified by the CIBSE TM59 standard, from 10 p.m. to 7 a.m.

Having identified the two rooms that will be studied, the interventions that were presented in the workflow will be considered in IESVE.

Primary energy assessment for cooling

After applying passive strategies to the model, considering the significant temperature increases over time, it will likely be necessary to implement an active cooling system. The calculation method to estimate the annual electricity consumption required to maintain an indoor temperature of 26°C, along with the associated costs, is outlined below.

To perform this calculation, the first step involves determining the thermal power (kW) needed to maintain 26°C in the studied rooms, which can be extracted from the dynamic simulations for the analyzed scenarios. Subsequently, the estimated annual electricity consumption (kWh) is calculated for both the base case and the scenario with the implemented strategies.

The annual energy consumption for the apartments studied is then estimated at 26°C during the summer period. Based on these values, the annual costs are calculated using an energy price of 0.35€/kWh. Finally, by comparing the energy costs of the base case and the scenario with shading and insulation, the potential savings are determined.

Results

The following sections present the simulation results for the two selected rooms under the current scenario, comparing both the baseline building configuration and the retrofit scenario incorporating all the strategies outlined in the workflow and summarized in Table 1.

Table 1: Summary of the strategies presented in the workflow

Intervention	Insulation of the building and double-glazed windows	Horizontal lamellas	Natural single side ventilation	Natural cross side ventilation	Ceiling fans
Activation	-	in the morning for SE room, when igh≥300 W/m² in the afternoon for NW room, when igh≥100 W/m²	from March to November for SE room from April to October for NW room	from May to August for both SE and NW room	when T≥28°C for both SE and NW room

Among the two shading systems evaluated, the results focus on the cases where lamellas are utilized, as they provide a representative understanding of the performance improvements achieved through the retrofit measures.
The discussion of the results focuses on the summer period, when the highest outdoor running mean temperatures are reached, as this is the most critical period due to climate change and the continuous rise in temperatures. This choice was also made because overheating problems are most critical for older people, since in winter the problem of excessive cooling can be more easily overcome thanks to the use of extra layers of clothing.
The first results reported are those related to the present scenario to compare the effectiveness of the passive strategies applied.

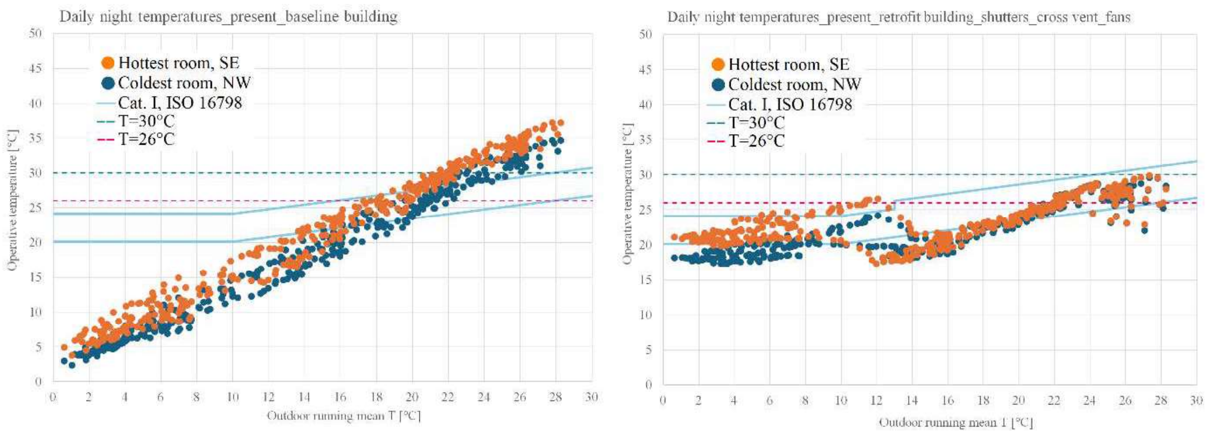

Figure 2a and 2b: Results in the present scenario.
On the left the results in the baseline configuration of the building, on the right the results in the retrofit configuration of the building with the presented strategies. Source: the author.

In the baseline configuration of the building, as shown in the chart on the left, most data points fall outside the comfort ranges. However, after implementing all the proposed strategies, as depicted in the chart on the right, during the hottest month of the year the majority of points fall within the acceptable limits. This improvement is partly attributed to the upward adjustment of the upper limits of the comfort categories, achieved through the use of ceiling fans [16].
This is because, thanks to the presence of the ceiling fan, it is possible to consider an air speed in the room that is different from zero and thus take into account the extended limits provided by the EN 16798 standard, which allows for an increase in the upper limits of the adaptive comfort categories to take into account the effect of air movement.
The standard provides for a different increase in comfort limits depending on air speed. In this case, an air velocity of 0,6m/s has been considered to take into account that the person in the room is not seated exactly under the center of the ceiling fan, but to the side [30].
Analyzing the results in detail, considering the upper limits of category I and the static limit of 30°C, there are few nights when the temperature reached is above these limits, making the two rooms suitable for the elderly and children aged 3 to 15 years. On the other hand, the two rooms are not suitable for infants in the summer period, as the static limit of 26°C is exceeded on 20% of the nights. In this scenario in the months of July and August the temperature does not fall below 26°C for up to 16 consecutive days.

During those months of the year when natural ventilation is not active, an air exchange of 0.15ach was guaranteed. A mechanical ventilation system would be useful to ensure air exchange and an optimal indoor temperature, but this choice was deliberately not considered as passive strategies are preferred given the energy poverty scenario.
After presenting the results for the present scenario, it is possible to move on to the future scenario to see whether the same strategies are equally effective, despite the different climate scenario.
The results obtained are shown below.

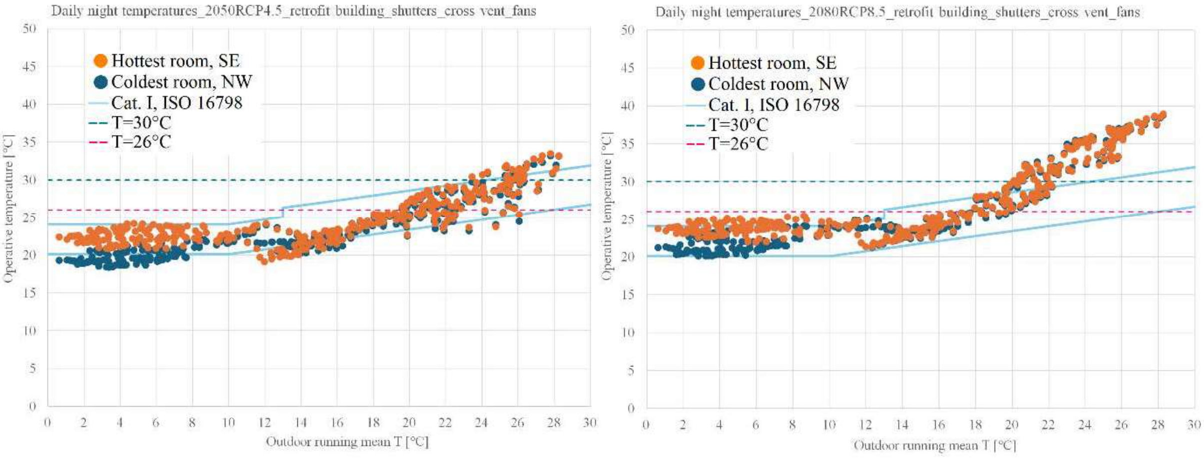

Figure 3a and 3b: Results in the two future scenarios.
On the left the 2050 rcp4.5 scenario, on the right the 2080 rcp8.5 scenario. Source: the author.

Analyzing the results for the two future scenarios considered, it is possible to see how, even if passive strategies are active and the limits are extended due to the presence of fans, in the hottest months of the year the number of dots within the limits of the first category is lower than before in both future scenario.
Going more in detail, starting to consider the intermediate scenario, 2050 RCP4.5, it is possible to see that the number of nights on which the temperature reached exceeds the upper limit of category I and the static limit of 30°C is much higher than in the present scenario, making the two environments suitable neither for the presence of the elderly nor for the presence of infants in the summer period. In particular, the percentage of nights in which the static limit of 30°C is exceeded in this scenario is 8% and the percentage of nights in which the static limit of 26°C is exceeded in this scenario is 28%. In this scenario, in the months of July and August the temperature does not fall below 30°C for up to 10 consecutive days.
Turning to consider the future worst-case scenario, 2080 RCP8.5, it is possible to see how temperatures increase significantly, reaching a percentage of nights when the static limit of 30°C is exceeded in this scenario is 22% and the percentage of nights when the static limit of 26°C is exceeded in this scenario is 36%. In this scenario in the months from June to September the temperature does not fall below 30°C for up to 99 consecutive days. Again, these two environments are not suitable for children and the elderly to stay in during the summer period.
In summary, when examining the timeline of interventions applied to the building, it is evident that, in the current scenario, these measures effectively ensure comfort, particularly for vulnerable groups such as children aged three to fifteen and the elderly, even during the summer months. However, in future scenarios, the effectiveness of these interventions diminishes due to the increasingly pronounced impact of climate change. Despite this, it is important to highlight that, although these interventions may not fully guarantee comfort in future conditions, they still contribute to significant temperature reductions in the two rooms analyzed.
Given that a cooling system is increasingly required across all scenarios, from the present to the 2080 RCP8.5 scenario, the estimated annual electricity consumption (kWh), costs (€), and savings (€) for the insulated case with shading were calculated, as outlined in the methodology chapter. The results are shown in the table below.

Table 2: Estimated electricity consumptions with the respective annual cost and saving in the three scenarios considering the summer season in the non-retrofit and retrofit case, source: the author

	Estimated electricity consumption per year [kWh]	Annual cost [€]	Annual saving with respect to the non-retrofit case [€]

	Flat	Presen t	2050	2080	Presen t	2050	2080	Presen t	2050	2080
Non retrofit	NW	899.7	1550.5	2276.6	314.9	542.7	796.8	-	-	-
	SE	1148.7	2227.5	3611.7	402.0	779.6	1264. 1	-	-	-
Retrofi t	NW	713.9	1225.3	1774.2	249.9	428.9	621.0	65.0	113.8	175.8
	SE	860.0	1845.1	2800.3	301.0	645.8	980.1	101.0	133.8	284.0

Conclusions

The study investigates long-term strategies for mitigating overheating in buildings housing vulnerable populations in the context of energy poverty. It aims to evaluate the effectiveness of passive strategies under future climate scenarios and determine the necessity of active cooling systems: these scenarios range from minimal climate change (RCP 2.5) to significant changes (RCP 8.5).

For the analysis, FWG software was used to generate climate data for Milan. The selected scenarios for the study included the current climate, a mid-range scenario for 2050 (RCP 4.5), and a worst-case scenario for 2080 (RCP8.5).

Simulations were conducted using the IES-VE software to evaluate the effectiveness of various passive strategies against adaptive comfort limits outlined in ISO 16798-1, as well as static temperature thresholds of 26°C and 30°C. The focus was placed on nighttime temperatures in two bedrooms, identified as the most thermally unfavorable rooms in the building. The simulations revealed that passive strategies are effective in the present climate scenario, however, for future scenarios, these strategies alone were insufficient to maintain comfortable temperatures. Active cooling systems were deemed necessary, especially in the worst-case scenario, 2080 RCP 8.5.

Energy consumption values related to the use of cooling systems were then calculated for each scenario, and it was possible to see that in the insulated case with shading the values were lower than in the base case, leading to savings not only in energy and money. This energy and cost saving also corresponds to a lower impact considering CO_2 emission levels, confirming once again that the retrofit case with the integration of passive strategies is the best choice.

In the Lombardy region, a significant number of buildings are classified as energy-intensive, primarily in classes G and F, with a high prevalence of elderly occupants. This underscores the broad applicability of the study's results.

Additionally, a user guide is provided in the following image, offering practical advice on improving thermal quality through passive strategies, aimed at helping residents enhance their living conditions in the face of evolving climate conditions.

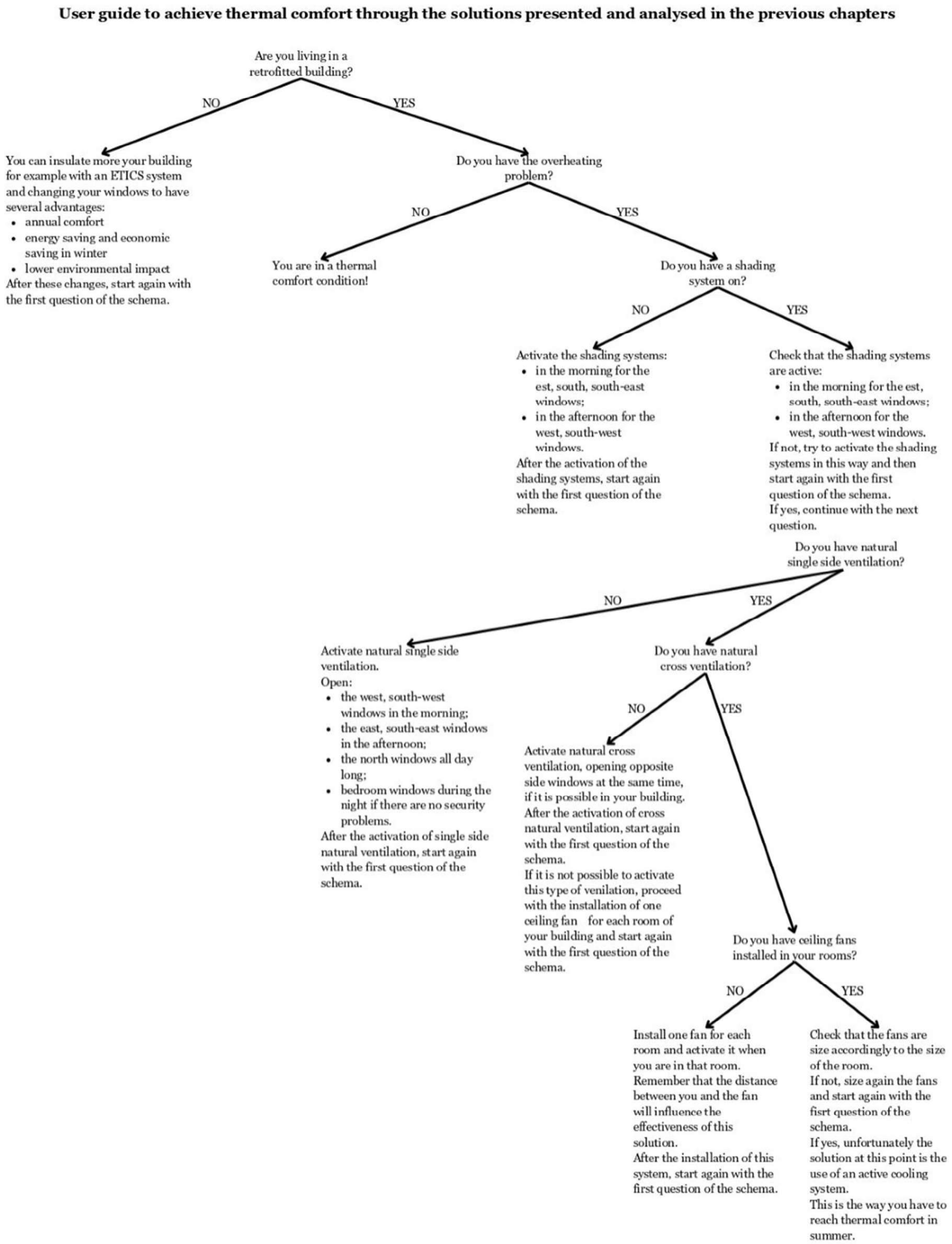

Figure 4: User guide to achieve thermal comfort through the presented solutions. Source: the author.

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